abc's of Radio-Frequency Heating

by

John Potter Shields

HOWARD W. SAMS & CO., INC.
THE BOBBS-MERRILL CO., INC.
INDIANAPOLIS · KANSAS CITY · NEW YORK

FIRST EDITION

FIRST PRINTING—1969

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Library of Congress Catalog Card Number: 76-98943

Preface

This book is intended to acquaint the technician and the experimenter with the technology of radio-frequency heating. Since first being put to practical use more than 40 years ago, radio-frequency heating has found increasingly wide acceptance—now reaching the point where it is finding myriad applications, ranging from heat treating of precision gears to the preparation of food in the home kitchen.

In the pages which follow, you will learn the basic concepts of radio-frequency heating, as well as the two different types of rf heaters: dielectric and induction. Domestic and industrial microwave ovens are covered, and an entire chapter is devoted to diathermy or "people heating." Also included is a description of radio-frequency plasma generation, one of the latest phases of radio-frequency heating. A chapter is devoted to applications of rf heating in light sources, welding, and surgery, and the book concludes with a chapter on servicing rf heating equipment.

Several practical projects, such as demonstration induction and dielectric heaters and a plasma torch, are included which are designed to further familiarize you with the basic devices of radio-frequency heating.

JOHN POTTER SHIELDS

Contents

CHAPTER 1

RADIO-FREQUENCY HEATING FUNDAMENTALS 7

Induction Heating—Dielectric Heating

CHAPTER 2

INDUCTION HEATING 14

The Oscillator Circuit—A Demonstration Induction Heater

CHAPTER 3

DIELECTRIC HEATING 29

Radio-Frequency Generator—Power-Line Filtering—Grounding —Work Electrode Types—A Demonstration Dielectric Heater

CHAPTER 4

POWER SUPPLIES FOR INDUCTION AND DIELECTRIC HEATERS . 40

Self-Rectifying Oscillators—Thyratron Power Control—Semiconductor Power Supplies

CHAPTER 5

THE MICROWAVE RANGE 47

A "State of the Art" Microwave Oven—The Tappan Microwave Oven—Other Microwave Ovens

CHAPTER 6

DIATHERMY 58

Operation of Diathermy Unit—Electrode Construction

CHAPTER 7

RADIO-FREQUENCY PLASMAS 64

A Plasma Generator—Induction Plasma Generator—Microwave Plasma Generators—Plasma Torch Operation—A Demonstration Plasma Torch

CHAPTER 8

MISCELLANEOUS RADIO-FREQUENCY HEATING APPLICATIONS 80

High-Intensity Radio-Frequency Light Source—Radio-Frequency Knife—Radio-Frequency Welding—Gas Ionization

CHAPTER 9

SERVICING RADIO-FREQUENCY HEATING EQUIPMENT . . . 86

Tools and Test Equipment Required—Measurement of Line Voltage—Checking Filament Voltage—Component Checking and Replacement—Tube Checking and Replacement—Plate and Filament Transformers—Timing Circuits and Controls—A Typical Servicing Case—Servicing Microwave Heating Equipment

INDEX 93

Chapter 1

Radio-Frequency Heating Fundamentals

In this chapter, we shall take a look at the basic principles of radio-frequency heating. There are two basic classifications of radio-frequency heating: induction heating and dielectric heating. Generally speaking, induction heating is employed in the heating of metallic materials, whereas dielectric heating is used in heating nonmetallic substances. Induction heating makes use of frequencies between roughly 60 Hz and 1 MHz, while dielectric heating may employ frequencies ranging from 10 MHz upward into the microwave region. The radio-frequency power levels in each case range from a few hundred watts to 100 kilowatts or more.

INDUCTION HEATING

In order to readily understand the principle of induction heating, consider Fig. 1-1. Here an iron-core transformer has its primary connected to a source of ac. Alternating current in the primary winding induces a current in the transformer secondary by electromagnetic induction. Note that the secondary winding is short circuited, which results in a very heavy cur-

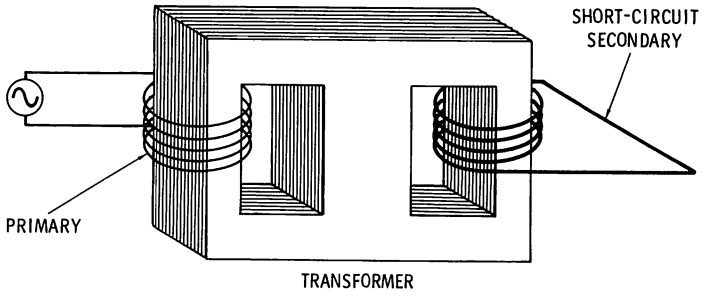


Fig. 1-1. Principle of induction heating.

rent through it. The heavy current through the transformer secondary results in heating of the secondary. This heating action is the basic principle of induction heating, although, in practice, radio-frequency energy is employed.

Now look at Fig. 1-2, which shows a basic radio-frequency induction-heating setup. The radio-frequency generator may be either a vacuum-tube oscillator or motor-generator unit. The latter is generally used when extremely large amounts of power are involved and when the operating frequency is less than 10 kHz.

The output from the radio-frequency generator is applied to the "primary" or "work coil," which consists of a number of turns of copper tubing, through which the work to be heated is placed. In operation, current through the copper-tubing primary induces very heavy currents in the material, which acts as a short-circuited secondary. The current induced in the secondary may be many thousands of amperes.

The frequency selected for radio-frequency induction heating is determined largely by the degree of heat penetration desired in the material being heated. For example, at very low

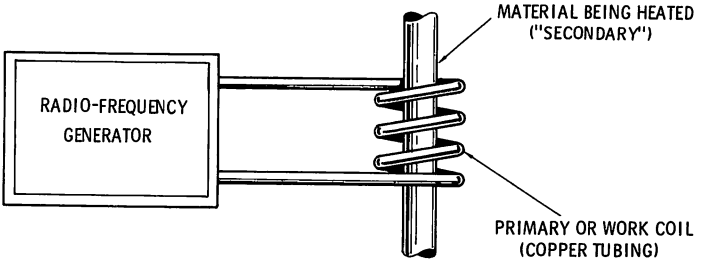


Fig. 1-2. Basic induction heater.

frequencies, say 60 Hz, the material will be heated essentially uniformly throughout. However, as the operating frequency is increased into the low radio-frequency range, the penetration of the heating decreases, with the heating occuring mainly at or near the surface of the material. As the applied frequency is increased further, this effect increases until almost all of the heating is concentrated at the surface of the material.

In high-power induction-heating systems, the copper-tubing primary is water cooled to remove heat generated by the large radio-frequency currents through it.

Fig. 1-3 shows a variation of the previously discussed induction-heating system. Here, induction heating is employed in soldering. As the material to be soldered passes under the induction-heater primary coil, a heavy current is induced in the material which causes it to reach the required soldering temperature rapidly.

Induction heating is also used to caseharden such items as gear teeth. As you perhaps know, for optimum service, a gear should have good physical strength, yet the mating surfaces of its teeth should be extremely hard in order to resist wear. To gain these properties, the gear teeth are subjected to a relatively high radio-frequency field which causes heating of the outer surface of the gear teeth. Thus the surface of the gear teeth is hardened, while the gear body is not affected.

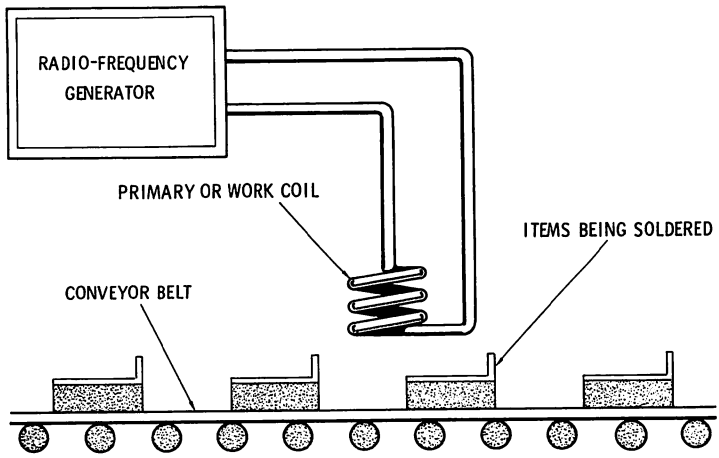


Fig. 1-3. Soldering by induction heating.

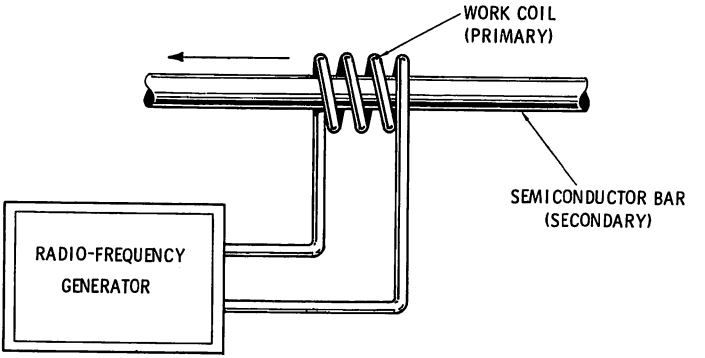


Fig. 1-4. Semiconductor refining by induction heating.

Induction heating is also employed in the purification (refining) of semiconductor materials. In a process known as *zone refining* a bar of germanium is slowly passed through the primary coil of an induction heater as shown in Fig. 1-4. As the germanium bar passes through the field of the primary, it melts, causing impurities within it to drift away. When the melted germanium hardens after passing through the field of the primary, it is substantially free of all impurities. In the following chapter, we will discuss the methods of induction heating in greater detail.

DIELECTRIC HEATING

Unlike induction heating, dielectric heating is used to heat nonmetallic substances. To readily understand the theory of dielectric heating, first refer to Fig. 1-5. Here a pair of metal electrodes is connected to the output of a radio-frequency generator. The material to be heated is placed between the electrodes. When radio-frequency energy is applied to the elec-

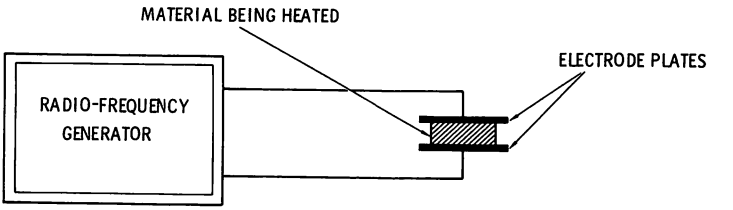


Fig. 1-5. Principle of dielectric heating.

trodes from the radio-frequency generator, a rapidly alternating electric field is established between the electrodes. This field penetrates the material between the electrodes. Under the influence of this rapidly alternating electric field, the molecules within the material rapidly reverse direction as they try to "keep in step" with the varying field. This to-and-fro molecular motion, due to the alternating field, results in "molecular heating" of the material.

For a given power input to the material being heated, the higher the applied frequency the greater is the amount of of heating. The reason for this is that as the frequency is increased, the rate of molecular motion is likewise increased. This increased rate in turn causes a more rapid heating of the material.

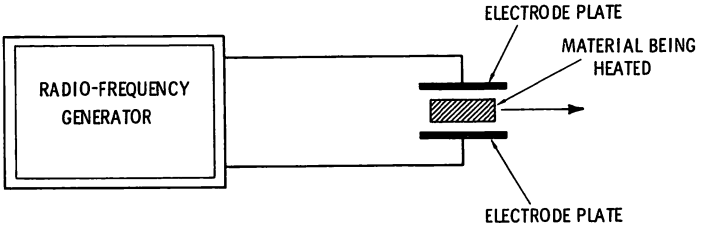


Fig. 1-6. Dielectric heating with electrode variation.

The amount of heating is also determined by how "lossy" the material is. For example, materials with considerable moisture content will absorb more radio-frequency energy, and hence they will heat up more rapidly. Good electric insulators, such as mineral oil, ceramic, glass, etc. show negligible response to dielectric heating.

Applying the RF Field to the Material

There are several basic methods of applying the radio-frequency energy to the material being heated. The most common method of applying the radio-frequency field to the material being heated is that shown in Fig. 1-5. Two metal plates (electrodes) are connected to the output of the radio-frequency generator, and the material to be heated is placed between the electrodes. A variation of this scheme, shown in Fig. 1-6, provides a slight spacing between the substance being heated and

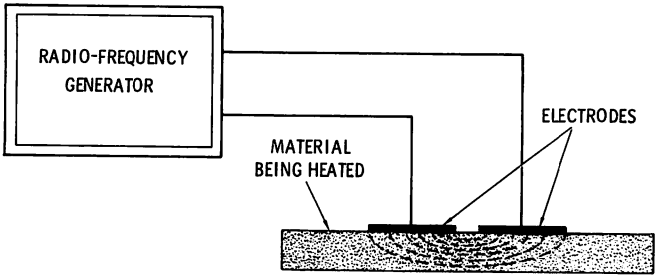


Fig. 1-7. Electrodes on the same side of the material.

the electrodes, the material then being continuously passed between the electrodes.

Another electrode arrangement is shown in Fig. 1-7. Here, both electrodes are placed on the same side of the material. This arrangement of the electrodes often allows more flexibility in heating.

When a greater heating area is desired, the setup shown in Fig. 1-8 may be employed. As shown, a number of individual electrodes are connected in parallel to provide a greater effective field-area presentation to the material which is to be heated.

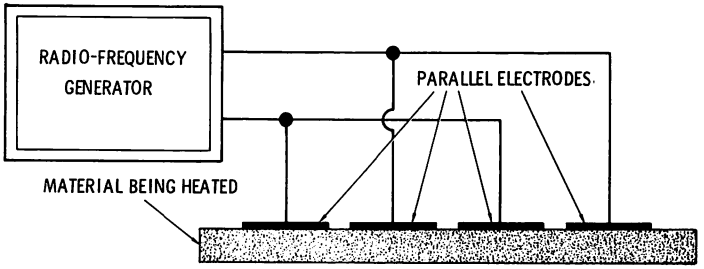


Fig. 1-8. Paralleling electrodes.

Heating With Microwaves

Uhf (microwave) radio-frequency heating is finding increasing use in dielectric heating—particularly in the area of food preparation.

Fig. 1-9 shows the basic arrangement of microwave dielectric heating. The source of microwave energy (usually a magnetron) is coupled to the material to be heated by means of a waveguide. The material to be heated is placed in a metal

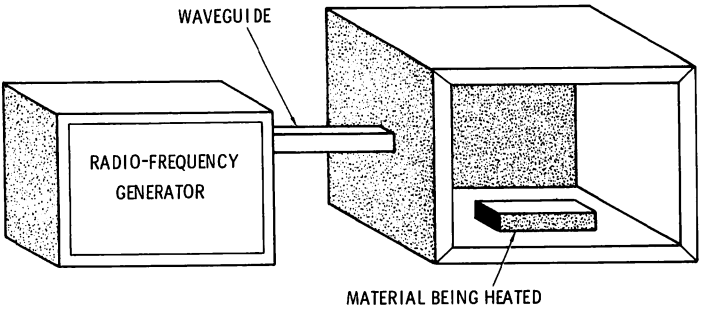
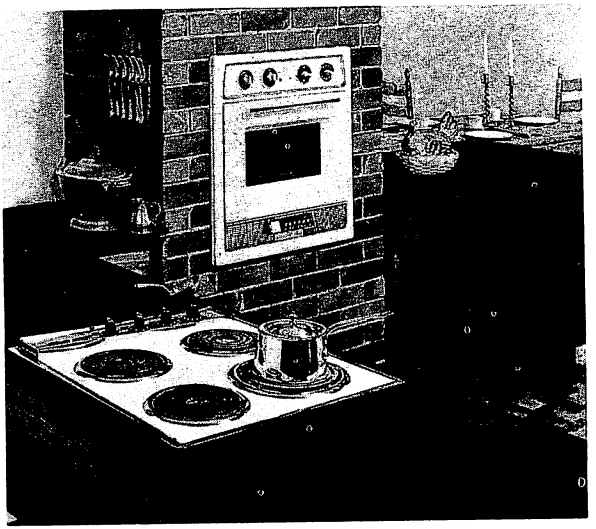


Fig. 1-9. Basic unit for microwave dielectric heating.

"cavity" as shown. The use of the cavity arrangement eliminates the need for electrodes as happened in the cases of the previously discussed systems.



Courtesy The Tappan Company

Fig. 1-10. Microwave oven for domestic use.

Fig. 1-10 is a photograph of a microwave oven which is used in domestic food preparation.

Chapter 2

Induction Heating

In this chapter, we are going to take a detailed look at induction heating. The various types of commonly used equipment, the circuitry involved, and the methods of operation will be examined. As mentioned in the previous chapter, induction heating is employed for metal heating.

The radio-frequency induction-heating apparatus consists of two basic parts: the radio-frequency generator which produces the required radio-frequency energy, and the work coil, into which, or near which, the material to be heated is placed. These two components are shown in Fig. 2-1.

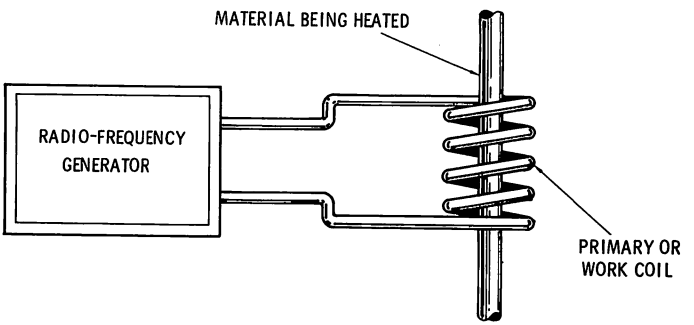


Fig. 2-1. Basic induction-heating setup.

THE OSCILLATOR CIRCUIT

The radio-frequency generator consists basically of a high-power vacuum-tube oscillator. Fig. 2-2 shows one type of oscillator circuit which is found in a typical radio-frequency induction heater. The oscillator tube, V1, along with L1, C1, C2, C3, and R1 form the basic components of the oscillator circuit. Basically the oscillator is of the shunt-fed Hartley type. Blocking capacitor C2 prevents the dc power-supply voltage from appearing on the tank coil, L1. The voltage drop across R1 provides the necessary negative grid bias for V1, while C3 serves as the grid dc-blocking capacitor. Transformer T2 provides the filament voltage for V1.

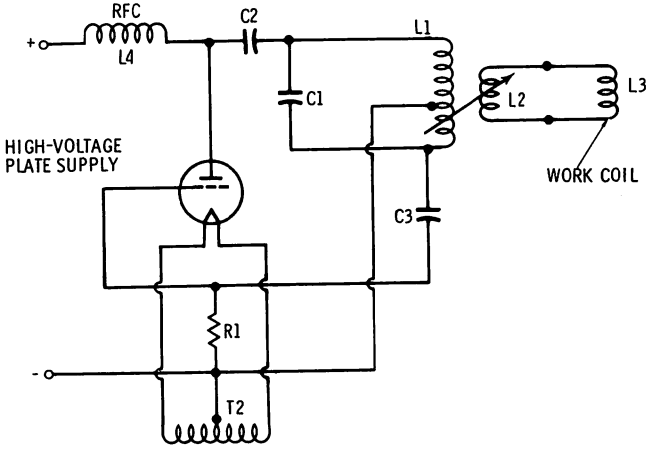


Fig. 2-2. Shunt-fed oscillator for induction heating.

The radio-frequency energy developed in the oscillator tank coil, L1, is coupled to the work coil, L3, by means of link pickup coil L2. As shown, the coupling between L1 and L2 is made variable to vary the amount of radio-frequency energy which is coupled to the work coil from the radio-frequency generator.

The radio-frequency choke, L4, prevents radio-frequency energy, developed by V1, from getting back into the power supply.

Fig. 2-3 shows another popular type of oscillator circuit. Basically a series-fed Hartley type, it is similar to the shunt-fed Hartley, except that the tap on the tank coil, L1, is returned

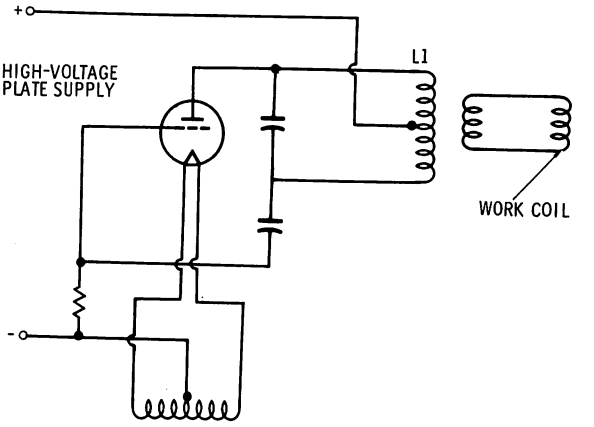


Fig. 2-3. Series-fed oscillator for induction heating.

to B + rather than to B − as in the case of the shunt-fed Hartley oscillator. This arrangement eliminates the need for a dc-blocking capacitor in the oscillator plate circuit. One disadvantage of the series-fed Hartley oscillator is that B + appears on the tank coil. However, if isolated link coupling is employed between the tank coil and work coil, this problem is eliminated.

Fig. 2-4 shows still another type of power oscillator which is used in industrial induction-heating equipment. Known as a push-pull oscillator, it employs two tubes, V1 and V2, in conjunction with L1, L2, C1, and R1. The tuned grid circuit, L2-C2, is set to resonate at the same frequency as the plate circuit, L1-C1. The rf energy in the plate circuit is fed back positively to the grid circuit via the internal grid-to-plate capacitances

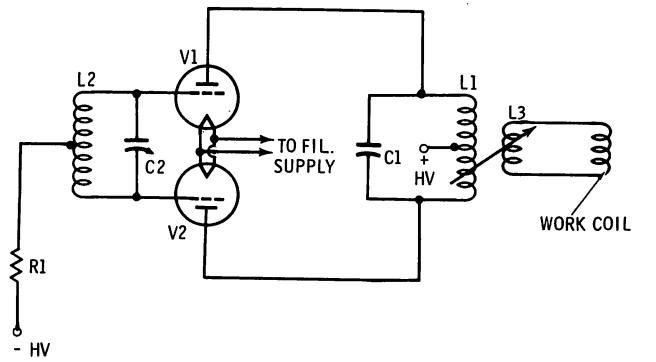


Fig. 2-4. Push-pull oscillator for induction heating.

of V1 and V2. This circuit may be recognized as being similar to that of a simple push-pull radio-frequency amplifier stage, the difference being that no neutralization is employed.

As in the case of the other oscillator circuits, radio-frequency output is taken from plate tank coil L1 by means of a movable link coupling coil, L3. One of the major advantages of the push-pull oscillator is that due to its balanced operation second-harmonic radiation of its fundamental output frequency is essentially eliminated.

Oscillator Components

Unlike the very low power oscillators found in receivers, signal generators and the like, oscillators used in radio-frequency heating generate large amounts of radio-frequency energy. As a result, special components are required in these circuits, some of which have rather unique characteristics.

Vacuum Tubes—The heart of the radio-frequency power oscillator is of course the vacuum tube. Almost without exception, a triode tube is employed in the interest of circuit simplicity.

The ratings of a tube employed as an rf power oscillator depend on the desired radio-frequency power output from the oscillator.

The major parameters of a triode tube used in a radio-frequency oscillator include:

1. Maximum plate dissipation.
2. Maximum plate voltage.
3. Maximum plate current.
4. Control-grid voltage.
5. Control-grid current.
6. Envelope and seal cooling requirements.
7. Filament-voltage limits.
8. Mounting position.
9. Maximum operating frequency.

The *plate-dissipation* rating of a vacuum tube refers to the maximum amount of power which the plate can dissipate in the form of heat, and is expressed in watts. The amount of energy dissipated by the plate can be determined by subtracting the amount of power delivered to the load from the dc plate power applied to the tube. The amount of power which can

safely be dissipated by a given tube is determined by the maximum allowable plate temperature as well as the seal and envelope temperature.

The term *maximum plate voltage* is self-explanatory; it refers to the maximum plate voltage which may safely be applied to the tube.

The *maximum plate current* rating denotes the maximum plate current for the tube and is generally referred to a given set of plate voltages.

The *maximum control-grid voltage* is generally expressed in both dc and ac peak values and differs from the nominal value of required dc control-grid voltage. This maximum control-grid voltage rating is particularly important when the tube is employed as a self-excited oscillator, because variations in loading may cause conditions in which the maximum control-grid voltage ratings are exceeded. This is particularly true in the case when the oscillator is lightly loaded.

The *maximum control-grid current* rating pertains to the maximum allowable grid current for a given control-grid dissipation.

Unlike receiving tubes which are cooled by simple convection, high-power vacuum tubes, due to the large amount of power which elements must dissipate in the form of heat, require additional means of removing this generated heat. Power tubes which have plate dissipation ratings of between 500 watts and 1000 watts are generally cooled by a stream of cooling air directed against their envelopes. The required amount of cooling air is denoted under "cooling-air requirements" in the manufacturer's specification sheet for the particular tube. Tubes with plate dissipation ratings much greater than 1000 watts are usually water cooled. Such tubes have external anodes which are placed in direct contact with the cooling water.

The *maximum element seal temperature* rating refers to the maximum safe seal temperature of the plate-connection (and often the grid-connection) seal. If this rating is exceeded, the seal may crack or separate, resulting in a loss of the vacuum within the tube.

The *mounting position* of a power tube is important and must be adhered to. For example, if the tube manufacturer states that the tube must be mounted in a vertical plane, base down,

and the tube is mounted horizontally, the tube filament might sag, causing an internal short and consequent destruction of the tube.

The *filament voltage* of a power tube must be held to within rather close tolerances if maximum tube life is to be expected. The maximum variation from the nominal value of filament voltage is specified by the tube manufacturer.

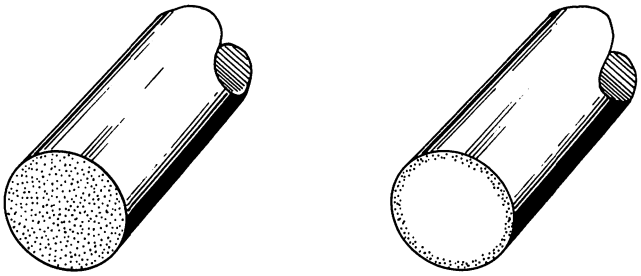
The *maximum operating frequency* of a power tube is specified by the manufacturer and denotes the maximum frequency at which the tube may be operated at full plate input. Generally, the tube may be operated at higher frequencies with reduced plate input. Often a derating curve is furnished by the tube manufacturer.

The preceding parameters are only for triode tubes. The reason for this is that tetrodes or pentodes are generally not used in radio-freqency heating equipment due to the increased circuit complexity which they require.

Capacitors—Capacitors employed in the tuning and coupling sections of radio-frequency power oscillators are usually either of the mica or ceramic variety. High-stability mica capacitors are generally employed in the tank circuit portions of the oscillator where good frequency stability is required. Ceramic capacitors are generally used in the coupling and bypass portions of the circuit. In addition to the usual capacitance and voltage ratings, capacitors employed in radio-frequency power oscillators usually have a "maximum rf ampere" rating. This rating refers to the maximum amount of radio-frequency energy which the capacitor can pass without exceeding its temperature rating due to excessive dielectric loss. For a given capacitor the higher the applied radio frequency, the lower is the rf ampere rating. This is due to the fact that there is an increased capacitor dielectric loss at higher frequencies, which results in a greater heating of the capacitor.

Resistors—Resistors used in radio-frequency power oscillators are usually of the wirewound type due to the considerable amount of power which they must dissipate. In some applications, noninductive resistors are employed.

Inductors—Plate tank inductors are generally made of copper tubing. Tubing is used rather that solid copper of the same diameter as at radio frequencies; the tubing offers essentially the same electrical conductivity, due to skin effect.



(A) Direct current. (B) Radio-frequency current.

Fig. 2-5. Distribution of charge carriers in conductors carrying dc and rf.

To understand this skin effect, take a look at Fig. 2-5, which shows two conductors. One conductor has rf current through it, while the other is carrying dc. Note that the two conductors have the same diameter. In the conductor carrying dc (Fig. 2-5A) all of the current carriers are evenly distributed throughout the conductor. On the other hand, the current carriers in the rf conductor (Fig. 2-5B) are mainly distributed at or near the surface. Thus, since the majority of current-carrying electrons in an rf-carrying conductor are near or at its surface, the conductor can be made hollow.

In very high power induction-heating systems, water is often circulated through the copper tank coil to avoid excessive temperature rise.

Radio-Frequency Chokes—Radio-frequency chokes in rf power oscillators are designed to present a high impedance to the rf signal developed by the oscillator, while readily passing the dc operating voltage. For proper operation the rf choke must be nonresonant at the oscillator operating frequency. Also, the choke must have low distributed capacitance, and it is to this end that many chokes have their windings arranged in "pies," as shown in Fig. 2-6.

Coupling Generator to Load

The radio-frequency generator must be coupled to the load, i.e., the material being heated. There are several methods of obtaining the most efficient transfer of energy.

Fig. 2-7 shows the most direct method of coupling the radio-frequency energy to the load. In operation, the work to be

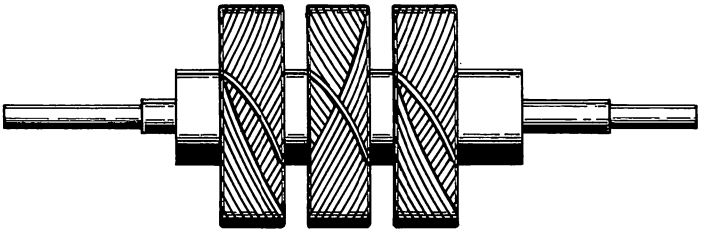


Fig. 2-6. Construction of pie-wound rfc.

heated is simply placed within the oscillator tank coil. This method of coupling energy from the oscillator to the load is not very satisfactory, for several reasons. First, the amount of energy applied to the work load cannot readily be varied, except by changing the position of the material within the tank coil. Second, oscillator loading will be uneven, thus resulting in possible oscillator instability and a chance of component damage. Third, placing the work directly within the tank coil restricts the physical configuration of work being heated.

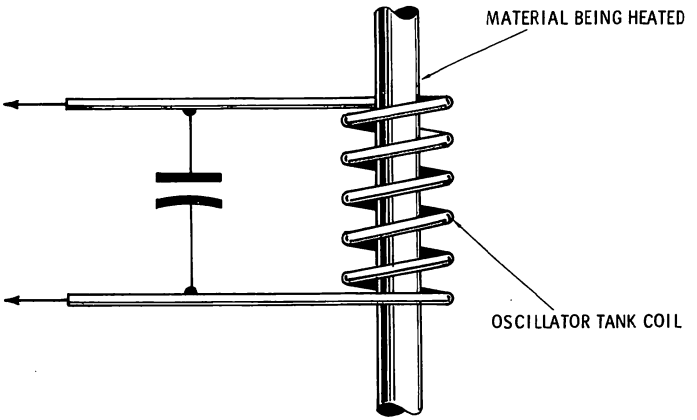


Fig. 2-7. Direct heating of material.

Fig. 2-8 shows a more acceptable method of coupling the radio-frequency energy to the work being heated. A link coupling coil, L2, is placed over the plate tank coil. The ends of L2 are connected to the ends of the work coil, L3. The material to be heated is placed within the work coil, L3. This method of coupling the radio-frequency energy from the oscillator to the work load has the advantage that the coupling between the

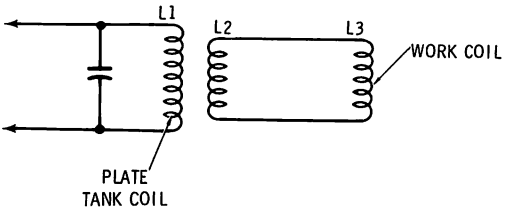


Fig. 2-8. Link-coupled work coil.

oscillator and load may be varied by varying the physical spacing between the oscillator tank coil and L2.

Fig. 2-9 illustrates another method of varying the coupling between the oscillator output and material without the necessity of physically varying the coupling. Capacitor C1, placed in series with L2 and L3, is adjusted to provide more or less coupling as desired.

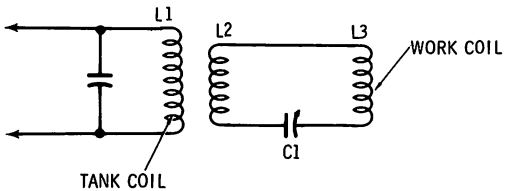


Fig. 2-9. Method of varying coupling between oscillator and work coil.

Work-Coil Design

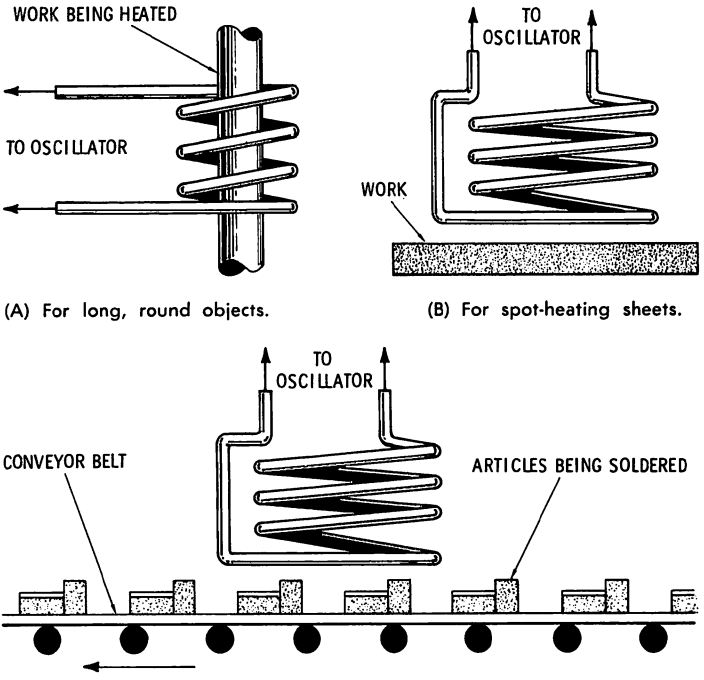
The design of the work coil in the induction heater is determined by a number of factors, including:

1. The physical configuration of the work to be heated.
2. The operating power level.
3. The type of heating desired.

The physical configuration—the size and shape—of the work being heated is of course a prime consideration in the design of the work coil. Fig. 2-10 shows several representative work coils. The coil shown in Fig. 2-10A is designed to heat long, round objects such as metallic rods, bars, etc. Often, in operation, the material to be heated is slowly passed through the work coil. In this way it can be uniformly heated over its entire length. This type of work coil is used in the zone refining of

germanium and silicon in the production of semiconductor devices.

Fig. 2-10B shows another form of work coil. In this instance the work coil is wound in a flat, pancake shape, with the work to be heated being placed directly under the coil. This type of work coil is often employed in the "spot-heating" of large metallic sheets as well as in radio-frequency soldering.



(A) For long, round objects.

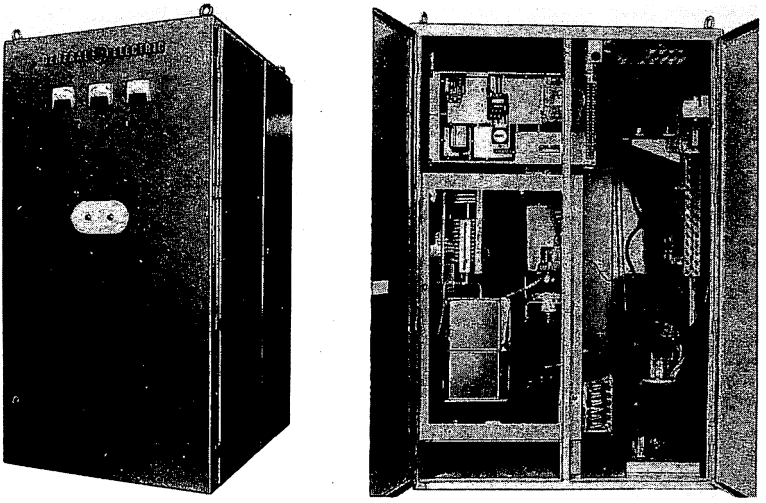
(B) For spot-heating sheets.

(C) For soldering on conveyor belt.

Fig. 2-10. Work-coil variations.

Fig. 2-10C shows a variation in which the articles being soldered are placed on a conveyor belt so that they are automatically heated to soldering temperature as they pass beneath the work coil. The conveyor belt speed and power applied to the work coil can be adjusted so that the articles on the belt reach just the right temperature in their exposure to the radio-frequency field.

The photograph of Fig. 2-11 illustrates two industrial induction heaters.



(A) GE industrial model. (B) GE model interior.

Courtesy General Electric Co.

Fig. 2-11. Typical industrial induction heater.

A DEMONSTRATION INDUCTION HEATER

This simple demonstration induction heater will graphically illustrate the basic operating principles of large commercial induction heaters. The unit is safe when operated by people with good sense, and it contains readily obtainable components.

As shown in Fig. 2-12, the demonstration induction heater consists of the power/isolation transformer, T1, oscillator tube V1, blocking capacitor C2, tank coil L1, tank capacitor C1, grid blocking capacitor C3, grid bias resistor R1, output link coupling L2, series blocking capacitor C4, and the work coil, L3.

In operation, an ac voltage of 120 volts is applied to the primary of the power/isolation transformer, T1. This voltage is stepped up to 1200 volts by the T1 high-voltage secondary winding. Filament voltage for the oscillator tube is supplied by a low-voltage winding on the same transformer.

The high voltage developed by the secondary of T1 is applied to the plate of V1 via the rf choke, L4, which prevents rf energy developed by the oscillator from reaching the high-voltage secondary of T1.

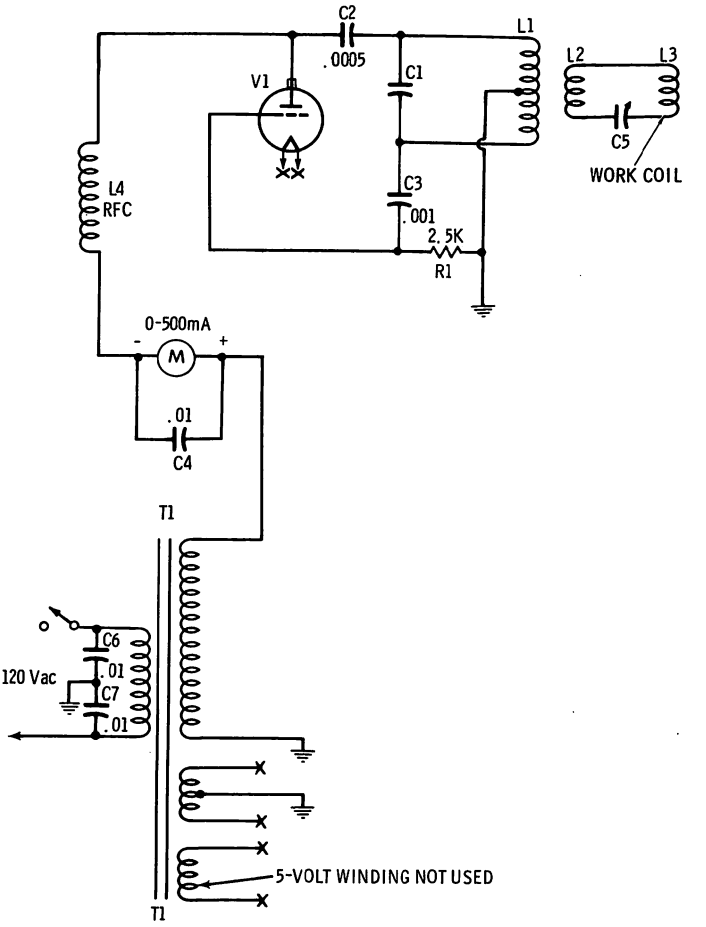


Fig. 2-12. Demonstration induction heater.

The plate blocking capacitor, C2, prevents the voltage applied to the plate of V1 from appearing across tank coil L1.

The plate tank coil, L1, consists of six turns of 3/8-inch soft copper tubing wound into a coil 3 inches in diameter. The spacing between turns is 1/4 inch. As shown in Fig. 2-13, the plate tank coil is supported on 2-inch ceramic cone insulators.

The plate tank capacitor, C1, consists of two 4-inch by 5-inch aluminum plates spaced 1/2 inch apart. As in the case of the tank coil, the plates are mounted on ceramic cone insulators as shown in Fig. 2-13.

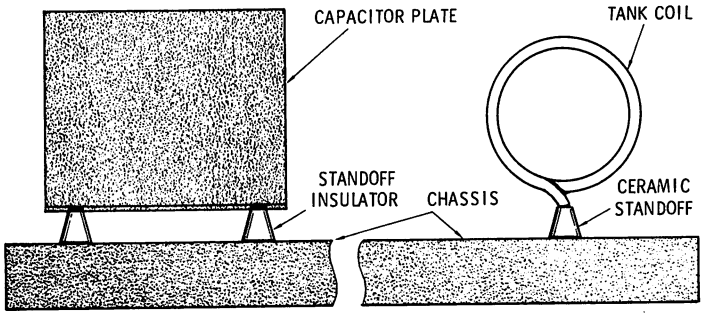


Fig. 2-13. Mounting of C1 and L1.

Fig. 2-14 shows in detail how the other circuit components are mounted on the chassis.

To check out the completed unit, place its line cord into a source of 120 volts ac and place the power switch to its ON position. The filament of V1 should light immediately, and the plate-current meter, M1, should indicate a plate current of approximately 50 mA. (The value of plate current may range anywhere from 30 to 70 mA.)

If the plate current is in excess of 100 mA, the oscillator is not operating properly and the tap on the tank coil should be readjusted to a different point on the coil. Be sure to remove operating power when making this adjustment. The position of

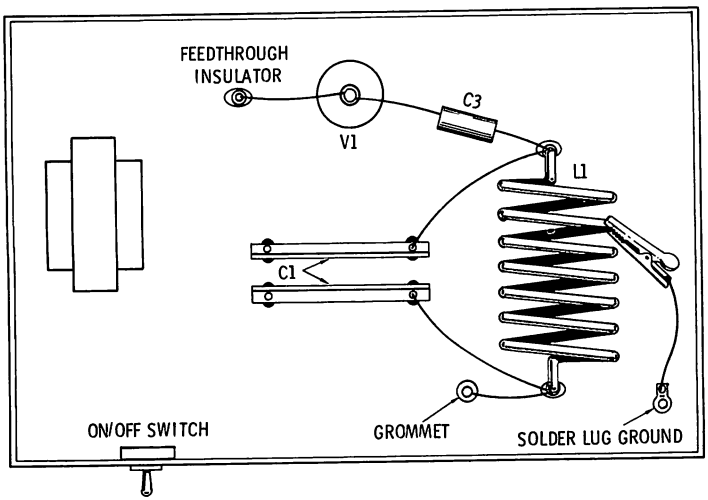


Fig. 2-14. Chassis layout.

Table 2-1. Parts List for Demonstration Induction Heater

Capacitors	
C1	(See text.)
C2	500-pF, 10-kV TV filter capacitor
C3	0.001-μF, 600-V disc capacitor
C4	0.01-μF, 600-V disc capacitor
C5	12-244-pF variable capacitor (Johnson No. 154-1)
C6, C7	0.01-μF, 600-V disc capacitors
Inductors	
L1	(See text.)
L2	3 turns ⅛" copper tubing wound over center of L1 (take care that L2 does not touch L1)
L3	3 turns ⅛" copper tubing, 3½" dia., supported on ½" or larger insulators
L4	2.5-mH rf choke
Meter	
M1	0-500-mA dc ammeter
Resistor	
R1	2.5-kΩ, 25-W wirewound resistor
Transformer	
T1	Stancor PC-8414 or equivalent
Tube	
V1	812A power triode

the plate tank coil tap which gives the lowest meter reading is the correct one.

With the oscillator adjusted for proper operation, place a piece of metal, such as a large screwdriver blade, through the center of L3. Be sure that the metal does not touch any of the turns of L3. Adjust the loading capacitor, C4, for the highest plate-current reading—around 140 mA. After the metal has been in place for a few seconds, quickly touch it was a moistened finger. You will find that the metal has become quite hot.

If proper loading cannot be obtained, the loading capacitor, C4, should be changed in value. The capacitor specified is correct for the majority of loads. If maximum loading occurs when the plates of C4 are wide open (minimum capacitance) additional capacitance is required. This additional capacitance

can be easily added by paralleling C4 with one or more 25-pF mica or ceramic capacitors with a voltage rating of 1000 volts or more.

Experimentation is in order with the demonstration induction heater. Try heating various types of materials, such as iron, steel, brass, aluminum, etc., noting the heating effects.

Chapter 3

Dielectric Heating

In this chapter we will turn our attention to dielectric heating. Dielectric heating, unlike induction heating, is used to heat nonmetallic materials, such as wood, plastic, chemicals, etc. The basic concept of dielectric heating is also quite different from that of induction heating.

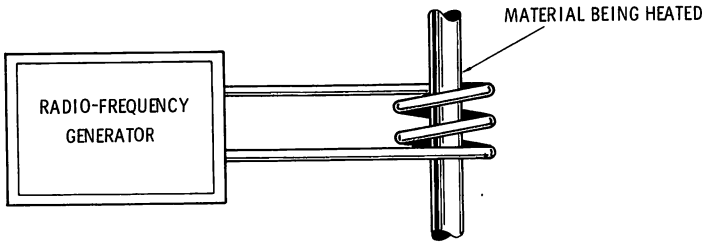
In induction heating the applied radio-frequency field induces eddy currents in the metal which cause the heating. On the other hand, dielectric heating results from the rapid motion of the molecules of the material while under the influence of the applied radio-frequency field. This rapid movement, or alternation, of the molecules causes "molecular heating," with the result of heating of the material.

In induction heating it is the magnetic radio-frequency field which does the heating, whereas in dielectric heating the eletric radio-frequency field does the heating. Whereas the work to be heated in an induction heater is placed in a "work coil," the dielectric heater makes use of metallic plates which apply the radio-frequency energy to the material placed between them. The difference between the two systems is shown in Fig. 3-1.

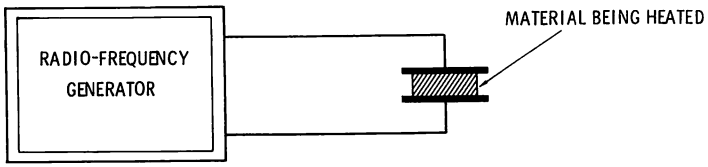
Dielectric heating derives its name from the characteristic in which the material being heated is much like the dielectric

of a capacitor, with the heating electrodes serving as the "plates" of the capacitor.

Fig. 3-2 is a block diagram showing the basic dielectric heater. The radio-frequency generator develops radio-frequency energy which is applied as a high radio-frequency voltage to the two electrode plates. This radio-frequency energy



(A) Induction heating.



(B) Dielectric heating.

Fig. 3-1. The difference between induction heating and dielectric heating.

appearing across the electrodes produces an rf electric field which penetrates the material placed between the plates. This rf electric field produces heating of the material in the manner described previously.

Now that we have seen the basic concept of radio-frequency dielectric heating, let us take a look at the various components involved.

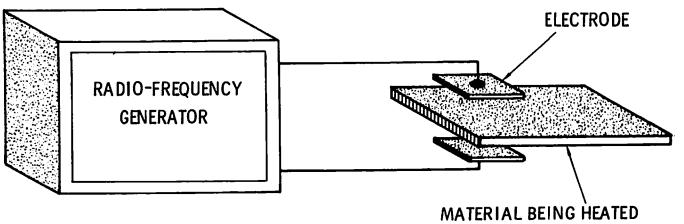


Fig. 3-2. Principle of dielectric heating.

RADIO-FREQUENCY GENERATOR

The heart of the dielectric heater is the radio-frequency generator. The purpose of the radio-frequency generator is to provide the radio-frequency electric field to the material being heated.

Unlike induction-heater radio-frequency generators, which usually operate in the frequency range of between 10 kHz to 1 MHz, dielectric-heater generators usually operate in the 30-MHz to 2400-MHz range. The power output for a medium-size dielectric-heater radio-frequency generator lies in the range of from 500 watts to 10 kilowatts or more.

Typical Dielectric-Heater RF Generator Circuitry

A typical dielectric-heater radio-frequency generator schematic appears in Fig. 3-3. The basic oscillator is of the push-pull, tuned-plate, untuned-grid design. This push-pull design

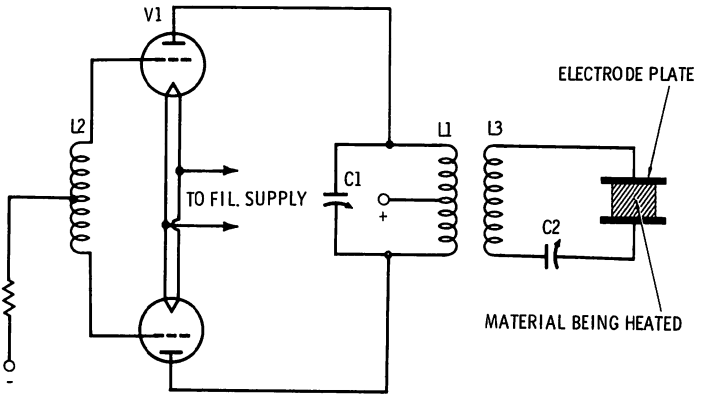


Fig. 3-3. Push-pull oscillator for dielectric heating.

is favored due to its symmetry—an important consideration at higher frequencies. Note that the circuit shown in Fig. 3-3 is similar to a triode rf power amplifier, although neutralization is omitted so that oscillation can take place by virtue of grid-to-plate feedback in the triodes.

The radio-frequency energy developed in the oscillator tank circuit, L1-C1, is coupled to the load by the link coupling, L3, which forms part of a series-resonant circuit in conjunction with C2 and the electrode plates.

In operation, with the material to be heated in place between the electrodes, capacitor C2 is adjusted for maximum transfer of energy to the load.

Fig. 3-4 shows another method of coupling the energy from the oscillator tank circuit to the load. Here, a parallel-resonant circuit is employed, with L2-C2 forming the parallel-resonant circuit in conjunction with the electrode plates. In operation, capacitor C2 is adjusted for maximum transfer of energy to the load.

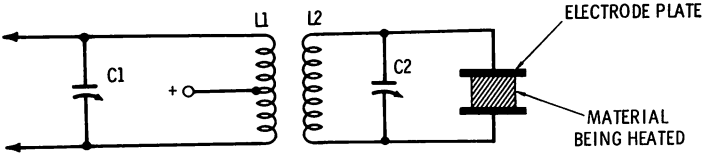


Fig. 3-4. Alternate method of coupling oscillator to load.

A variation of the circuit of Fig. 3-4 is shown in Fig. 3-5. Here, the parallel-resonant circuit is formed between C2 and the portion of coil L2 between points A and B. The electrode plates are connected between points A and C. This arrangement provides a voltage step-up by autotransformer action of the coil between points B and C. This setup is useful in providing a high radio-frequency electric field to the material being heated without requiring that resonating capacitor C2 have an extremely high voltage-breakdown rating.

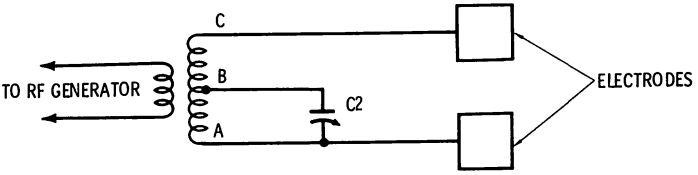


Fig. 3-5. Autotransformer resonant circuit.

Fig. 3-6 shows another type of oscillator which is used in radio-frequency dielectric heaters. It is of the series-fed Hartley type. Since the dc power-supply voltage appears on the tank coil, link coupling is employed to prevent the power-supply voltage from appearing at the electrode plates.

A variation of this circuit is shown in Fig. 3-7. Known as a shunt-fed Hartley oscillator, it has an advantage over the

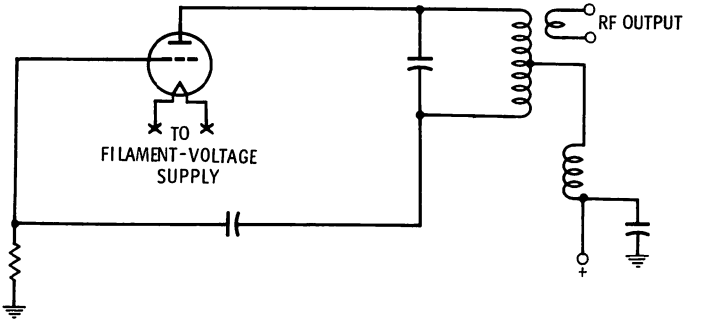


Fig. 3-6. Series-fed Hartley oscillator.

series-fed Hartley type in that a blocking capacitor prevents the dc plate-supply voltage from appearing across the oscillator plate tank coil.

Fig. 3-8 shows an oscillator circuit which is applicable to frequencies in the range of from 300 to 900 MHz. Known as a resonant-line oscillator, it makes use of a resonant quarter-wave transmission line in place of the more conventional lumped-constant LC tank circuit which is used in lower-frequency oscillators.

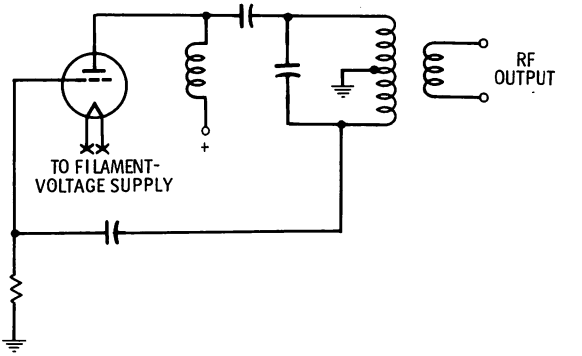


Fig. 3-7. Shunt-fed Hartley oscillator.

The advantage of the resonant-line oscillator is evident when it is considered that at frequencies much above 200 MHz the conventional coil-capacitor tank circuit becomes inconvenient and difficult to design due to the vary small values of inductance and capacitance required to resonate at these high frequencies. Also, these extremely small values are often

"swamped out" by other circuit elements, such as stray inductance and capacitance which may be inherent in the circuit.

On the other hand, at 300 MHz, a quarter-wave resonant line is approximately 10 inches long. This physical length can be easily handled and is much more practical than a conventional inductance-capacitance tank circuit at this frequency.

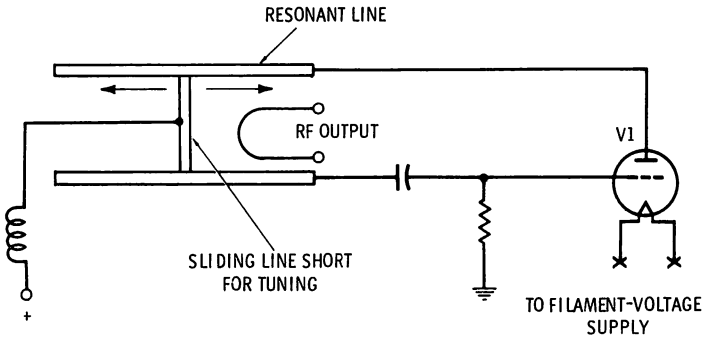


Fig. 3-8. Resonant-line oscillator.

Tuning of the resonant-line oscillator is accomplished by means of a shorting bar which can be moved along the parallel lines to lengthen or shorten them electrically, as shown in Fig. 3-8. As the shorting bar is moved closer to the grid and plate terminals of V1, the lines are electrically shortened, and as a consequence the oscillator operating frequency is increased. Conversely, as the shorting bar is moved away from the grid and plate terminals, the oscillator operating frequency will be lowered.

Oscillator Shielding

Most modern dielectric-(and induction-) heater radio-frequency generators are designed to have a minimum of spurious radio-frequency radiation in order to minimize interference with other electrical and electronic equipment.

The most important consideration in the reduction of radiation is the proper electrical shielding of the oscillator proper. To this end the oscillator tube and associated components are usually placed inside a grounded metal enclosure to reduce radiation from these components.

The reduction of harmonic signal radiation may be accom-

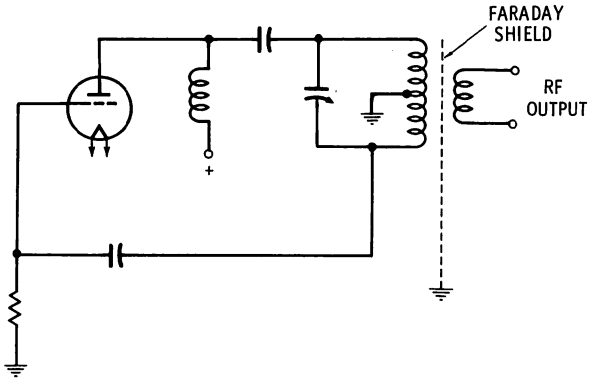


Fig. 3-9. Faraday shield reduces harmonic radiation.

plished by a so-called Faraday shield which is placed between the oscillator plate tank coil and output line coupling as illustrated in Fig. 3-9. This Faraday shield has the property of passing the magnetic energy between the oscillator tank circuit and link, while blocking the electric component of the radio-frequency signal.

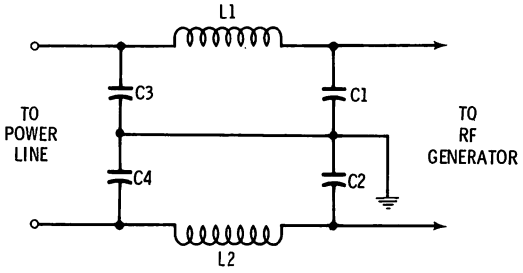


Fig. 3-10. Rf line filter reduces rf radiation.

POWER-LINE FILTERING

In addition to the previously mentioned method of reducing radio-frequency spurious radiation from radio-frequency generators, provisions must also be made to reduce radiation from the power line feeding input power to the oscillator.

One of the most effective methods of reducing radio-frequency radiation from the power line is shown in Fig. 3-10. Known as line filtering, it effectively bypasses radio-frequency energy appearing on the line to ground.

The main requirements of this type of filter are that the series radio-frequency chokes, L1 and L2, have sufficient inductance to offer a high impedance to the radio-frequency signal appearing on the line, while offering negligible opposition to the line current into the oscillator circuitry. The shunt capacitors, C1, C2, C3, and C4, must have a low reactance at the oscillator operating frequency and a dc voltage rating higher than that of the line voltage appearing across them.

GROUNDING

Proper external electrical grounding of the radio-frequency generator circuitry is essential for maximum reduction of spurious radio-frequency radiation. By "proper" radio-frequency grounding is meant that the generator cabinet and all "grounded" portions of the generator circuitry be connected to a good external earth ground. Such a ground can be obtained from a cold-water line or metal stake driven into moist earth. Many industrial installations are available with grounding buses to which equipment may be connected to provide the necessary grounding.

WORK ELECTRODE TYPES

Once the radio-frequency energy is developed by the radio-frequency generator it must be suitably applied to the work load to be heated. Proper design and application of the "work electrodes" is all-important to proper operation of the dielectric-heating system.

Fig. 3-11 illustrates the simplest of work electrodes. Two metallic plates are placed on opposite sides of the material to be heated. The plates are connected to the radio-frequency generator by a suitable matching network such as described

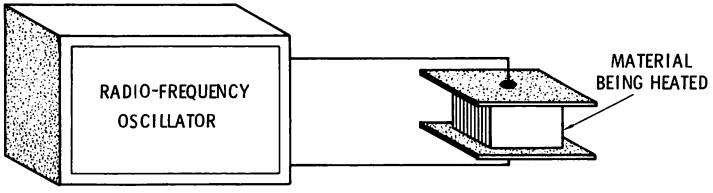


Fig. 3-11. Parallel electrodes.

previously in this chapter. When radio-frequency energy is applied to the electrodes, the energy flows into the material, causing it to become heated. It is not necessary that the two electrode plates actually touch the material; a slight spacing between the plates and material being heated will provide satisfactory results in most cases.

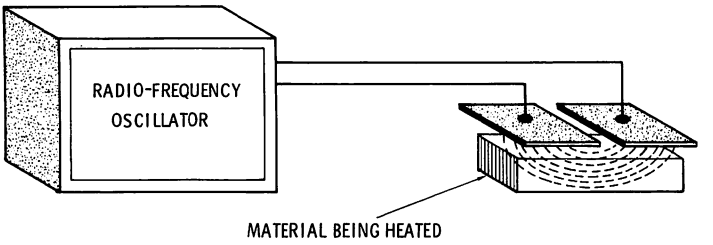


Fig. 3-12. Spray-field heating.

Fig. 3-12 shows another method of electrode arrangement. Here, both of the work electrodes are placed on the same side of the work. This method is sometimes called "spray-field" heating, and has the advantage that both electrodes are on the same side of the work. The field is shown by the dotted lines. Fig. 3-13 shows the situation in which the work to be heated is passed beneath the work electrodes on a conveyor belt.

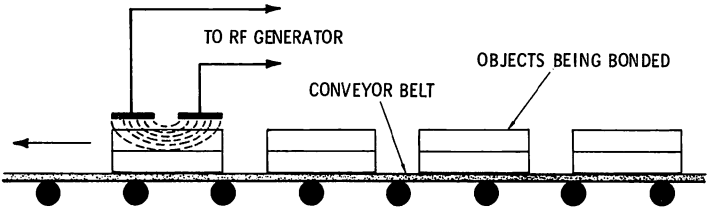


Fig. 3-13. Using coplanar electrodes for heating moving objects.

Fig. 3-14 shows still another method of electrode arrangement. In this case the electrodes consist of rollers, between which the work is passed. This setup may be combined with pressure rollers so that the work is squeezed together as it is being heated. This arrangement is often used in the continuous bonding of wood veneers.

The work electrodes may also be combined into a press as shown in Fig. 3-15.

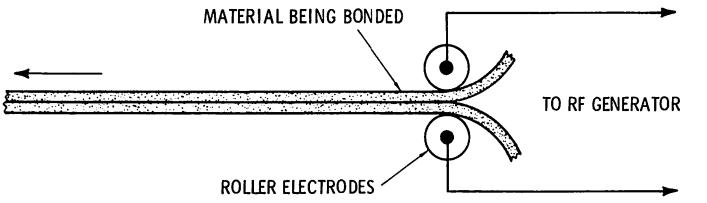


Fig. 3-14. Roller electrodes for continuous bonding.

Only a relatively few variations of work electrodes have been described—many other configurations may be used.

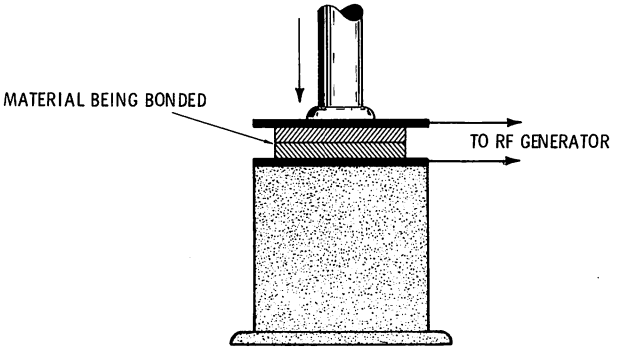


Fig. 3-15. Electrodes combined with press.

A DEMONSTRATION DIELECTRIC HEATER

This simple demonstration dielectric heater will graphically demonstrate the basic principles involved in dielectric heating.

The demonstration induction heater described in Chapter 2 is used in this demonstration dielectric heater. Fig. 3-16 shows the required modifications. The tank-circuit link coupling, L2, consists of two turns of 1/4-inch OD copper tubing

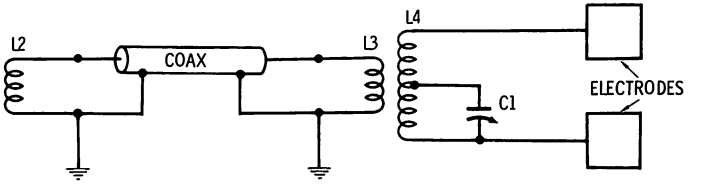


Fig. 3-16. Loading and coupling coils for demonstration dielectric heater.

placed around the center of the plate tank coil. The ends of this link are coupled to the work link coupling, L3, by a length of RG/8U coaxial cable. The impedance-matching coil, L4, consists of ten turns of 1/4-inch OD copper tubing 2 inches in diameter. Coil L3 is placed in the center of L4.

The "loading" capacitor, C1, is a 100-pF transmitting-type capacitor with a voltage rating of at least 3 kV. The electrodes consist of two 4-inch by 4-inch aluminum plates, spaced approximately 2 inches apart.

A good way to check out the operation of the demonstration dielectric heater is to place two pieces of wood glued together between the electrodes, apply power to the oscillator, and adjust the "loading" capacitor for a maximum plate-current reading. After a few minutes of operation, remove the two pieces of wood from between the electrodes. You will find that the glue has set, firmly joining the two wood pieces together.

In operating the unit you may find that you cannot get maximum oscillator loading for any setting of the loading capacitor. If maximum loading occurs with C1 set at maximum capacitance, increase the number of turns in L4. Conversely, if maximum oscillator loading occurs at minimum setting of C1, then decrease the number of turns in L4. A little experimentation here will be in order.

Chapter 4

Power Supplies for Induction and Dielectric Heaters

In this chapter we are going to examine the various types of power supplies which are employed in industrial induction- and dielectric-heating equipment. You will note that the design of these power supplies differ in many respects from those found in low-power equipment, though the basic functions are the same.

SELF-RECTIFYING OSCILLATORS

Many of the oscillator circuits employed in radio-frequency generators (both induction and dielectric) employ no rectifiers to convert the high-voltage plate supply to dc. Instead, the oscillator is operated directly from the high-voltage secondary winding of the plate-supply transformer. Such an oscillator arrangement is shown in Fig. 4-1.

The high voltage developed across the secondary of the plate transformer, T1, is applied directly to the plate circuit of the oscillator tube, V1, through the rf choke, L1. In operation,

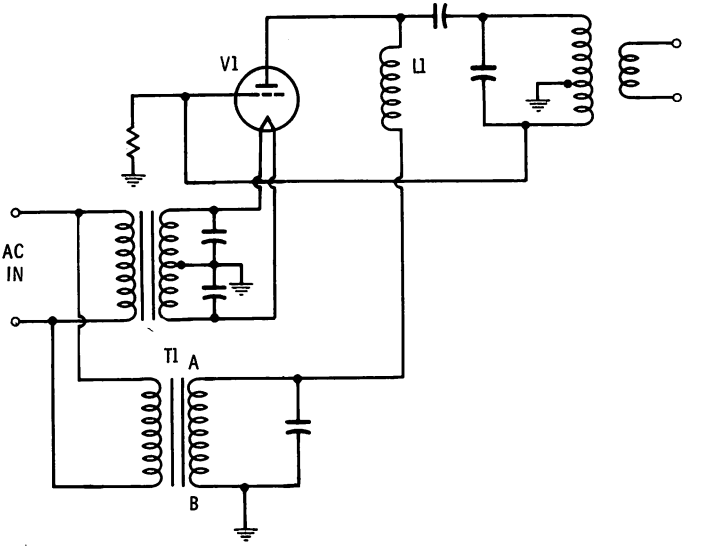


Fig. 4-1. Self-rectifying oscillator.

when the top of the secondary of T1 (point A) is positive with respect to point B, the plate of V1 is positive with respect to its filament. As a result, plate current will flow and the circuit will oscillate. On the next half-cycle, the plate of V1 is negative with respect to its filament and the circuit will not oscillate.

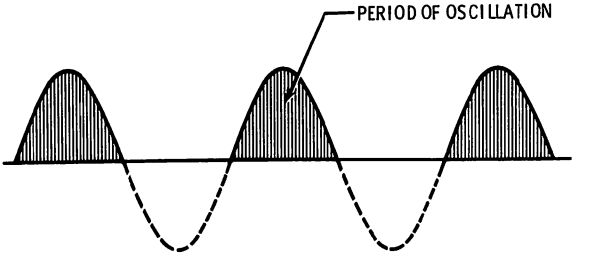


Fig. 4-2. Output waveform of self-rectifying oscillator.

As a result the output from the oscillator will appear as shown in Fig. 4-2: a series of pulses. The average radio-frequency output from this arrangement will be slightly less than one-half that which would be obtained if the oscillator were supplied from a conventional full-wave rectifier system. The chief advantage of the self-rectifying oscillator is its simplicity.

Fig. 4-3 shows an rf generator oscillator fed from a full-wave unfiltered power supply. Note that no filtering system is employed; it is unnecessary in this type of service. Notice that mercury-vapor rectifiers are employed in the circuit of Fig. 4-3. This type of rectifier is used due to its ability to withstand the high operating voltages generally employed in radio-frequency power oscillators. Also, the voltage drop across a mercury-vapor rectifier is quite low, being on the order of only a few volts. This leads to increased rectifier efficiency. Semiconductor rectifiers are also employed in this type of rectifier service.

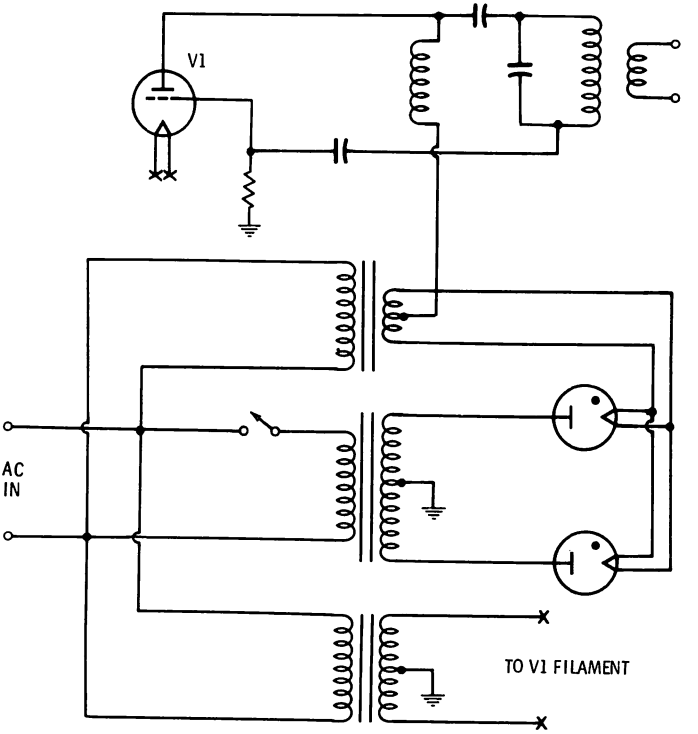


Fig. 4-3. Full-wave unfiltered power supply.

THYRATRON POWER CONTROL

Thyratron tubes are often employed in the rectifier portions of high-power radio-frequency power oscillators as a means

of readily controlling the amount of power applied to the oscillator and hence the amount of radio-frequency energy delivered to the load being heated. Before examining the thyratron power supply proper, let us take a look at the basic operation of the thyratron rectifier.

Fig. 4-4 is the schematic representation of a triode thyratron tube, which consists of a heater, cathode, control grid, and plate. The thyratron envelope is filled with neon, argon, or zenon.

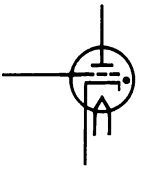


Fig. 4-4. Thyratron triode tube.

One basic characteristic sets the thyratron apart from the high-vacuum tube: Once plate current has been initiated, it will continue until plate voltage has been reduced to essentially zero. With plate voltage initially applied to a thyratron, and the control grid maintained at a sufficiently high negative voltage with respect to the cathode, the thyratron will not conduct plate current. If the thyratron control grid is now

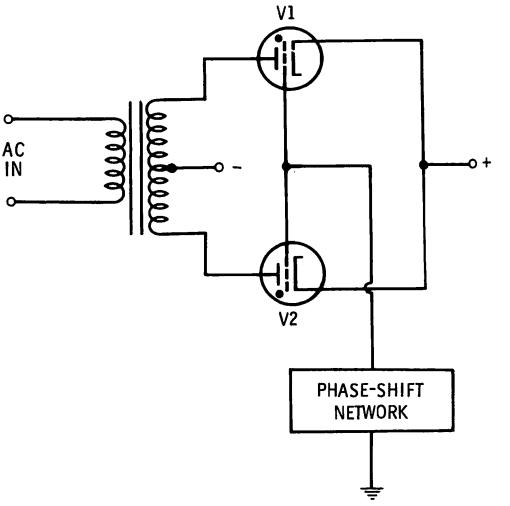


Fig. 4-5. Basic phase-controlled thyratron power supply.

dropped to zero volts with respect to the cathode, plate current will suddenly flow. Once plate current flows, the control grid loses all control over it. This is unlike the behavior of the high-vacuum tube in which the control grid maintains control of the plate current at all times.

With this understanding of thyratron electrical characteristics, let us consider how it may be used to control the dc power supply of the radio-frequency power oscillator.

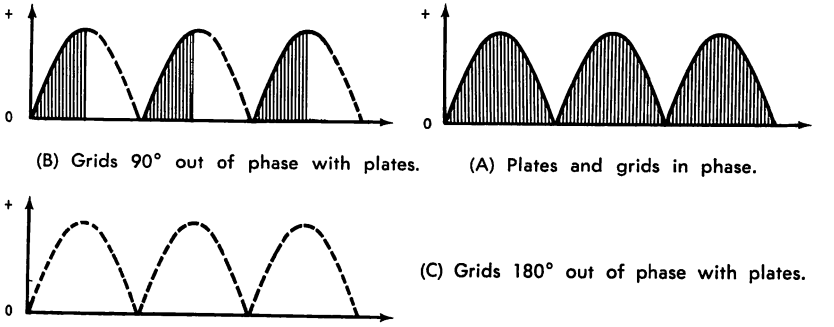


Fig. 4-6. Output current of phase-controlled power supply.

Fig. 4-5 shows the arrangements of a basic phase-controlled dc power supply. The control grids of thyratrons V1 and V2 are connected to the output of a phase-shifting network, this serving as the voltage-controlling device.

To understand the operation of the phase-shifting network in controlling the thyratron, refer to Fig. 4-6. For Fig. 4-6A the control grids of V1 and V2 are in phase with their respective plates. Under these conditions, plate current will flow as indicated. For Fig. 4-6B the phase-shifting network is adjusted

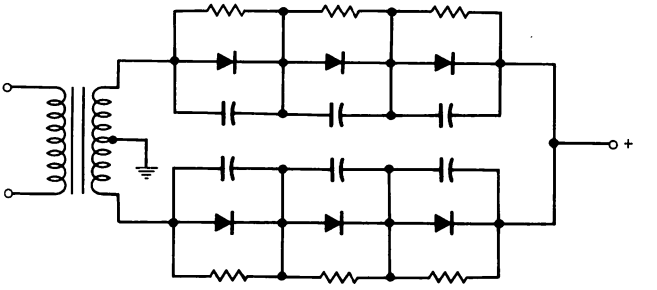
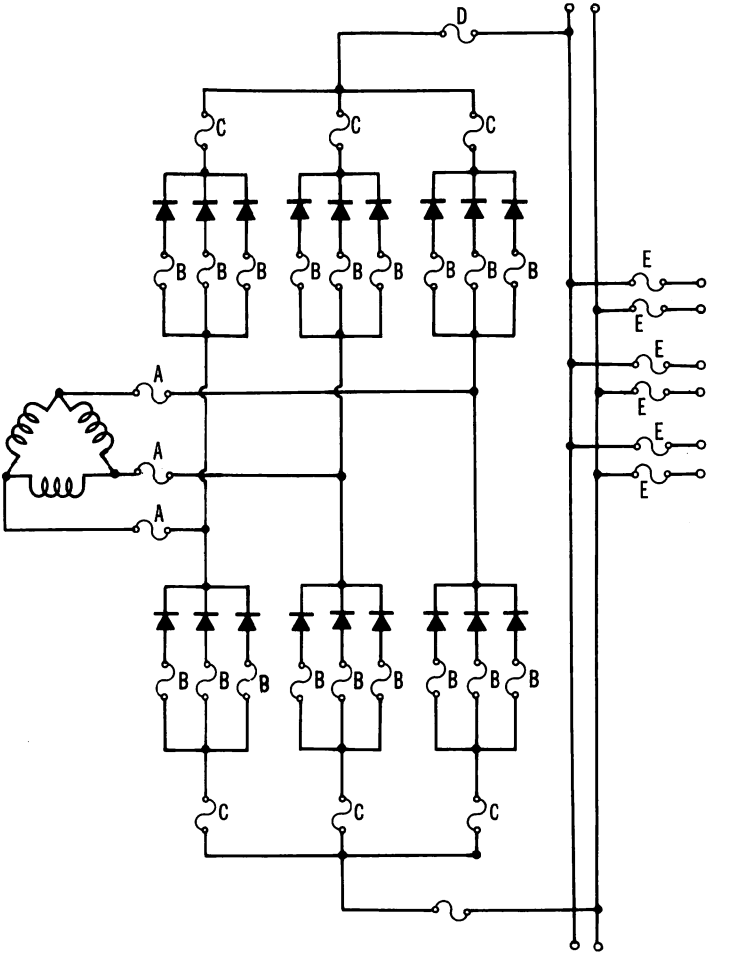


Fig. 4-7. Semiconductor power supply.

so that the grids of V1 and V2 are 90 degrees out of phase with their respective plates; the resulting waveform is shown. For Fig. 4-6C, the control grids of V1 and V2 are 180 degrees out of phase with the plates, and as a result there is no output. The amount of average power delivered to the load from the power supply is a function of the length of each half-cycle that the thyratrons conduct.

The advantage of the thyratron control is that negligible power is consumed in the controlling circuit.



Courtesy Motorola Semiconductor Products, Inc.

Fig. 4-8. Three-phase rectifier system.

SEMICONDUCTOR POWER SUPPLIES

An increasing number of radio-frequency heating generators are adopting semiconductor diode rectifiers. Semiconductor rectifiers offer a number of advantages compared with gas-filled tubes, including smaller physical size, greater mechanical ruggedness, longer operating life, and lower voltage drop.

Since single semiconductor diodes are not generally available with breakdown-voltage ratings equal to those of the gas-filled tubes employed in radio-frequency generators, it is necessary to series connect a number of individual semiconductor diodes to obtain the required voltage rating. How this is done is shown in Fig. 4-7. Note that resistors are connected across each diode. The purpose of these resistors is to equalize the voltage drop across the individual diodes to compensate for minor differences in diode characteristics. The capacitors which are also connected across the diodes serve to bypass any voltage transients which could destroy the diodes.

POLYPHASE POWER SUPPLIES

High-power (10 kW or more) radio-frequency generators are often designed to operate from three-phase power lines. The reason for this is that greater efficiency can be realized.

Fig. 4-8 shows a typical three-phase rectifier system employing semiconductor diodes as rectifiers.

Chapter 5

The Microwave Range

In this chapter, we are going to examine the use of microwave energy as applied to the cooking of food. The advantages of microwave cooking as compared with "conventional" methods include speed, the preservation of natural flavors, and the preservation of nutrient values to name a few.

Fig. 5-1 shows the basic approach to microwave cooking. The food to be cooked is placed in an "oven" which in reality is a microwave cavity. Microwave energy is conducted to the cavity by means of a waveguide which in turn is fed by the source of microwave energy, usually a magnetron tube. In some microwave ovens a triode is used in place of a magnetron to generate the required microwave energy, though the magnetron is more commonly used.

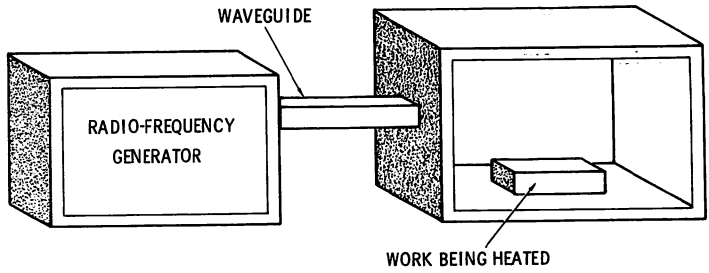


Fig. 5-1. Basic microwave heating.

When the microwave energy strikes the food within the oven cavity, the food absorbs the microwave energy, converting it into heat. Since the heat is generated inside the food, cooking time is much less than by ordinary means. As an example, a potato can be baked in a matter of minutes, bacon fried to a turn in 30 seconds or so, and a small roast cooked in 30 minutes. The actual microwave power developed in the average domestic microwave oven varies from 500 watts to 3 kilowatts. About 1 kilowatt is considered average.

Before continuing further with precise details of microwave oven operation, it is advisable to examine in some detail the basic operation of the magnetron tube, as it is this type of tube which is almost exclusively employed in microwave ovens.

To grasp the basic operation of the magnetron, look at Fig. 5-2, which shows a heated cathode surrounded by a cylindrical anode. Since the anode is positive with respect to the cathode, electrons will flow from the cathode to the anode as is the case of any thermionic diode.

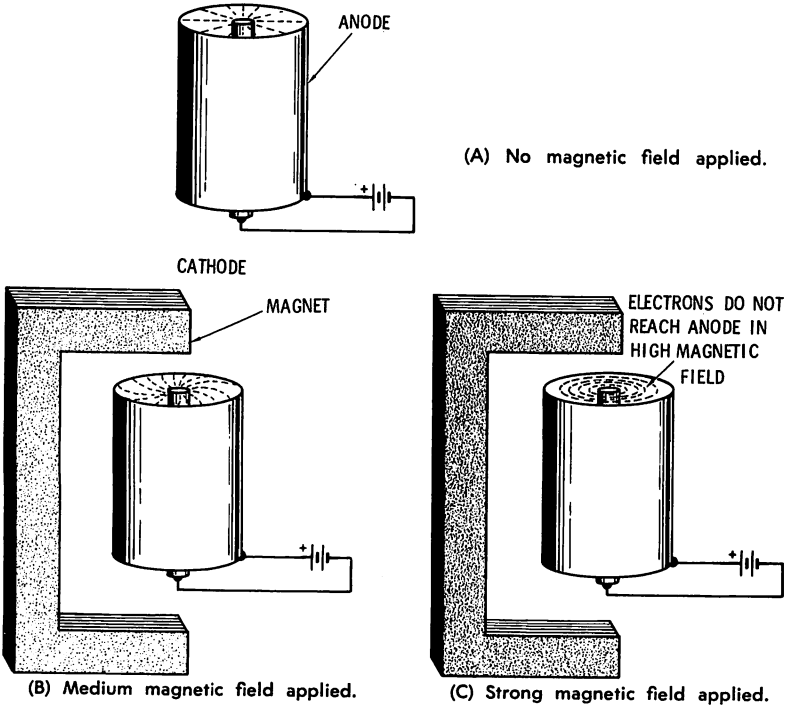


Fig. 5-2. Basic operation of magnetron.

In Fig. 5-2B, the same diode is placed in a magnetic field. Notice that now, instead of going straight from cathode to anode, the electrons emitted from the cathode take a curved path on their journey from cathode to anode. If the magnetic field is increased still further, the electrons will travel in tighter spirals around the cathode, never actually reaching the anode, as depicted in Fig. 5-2C.

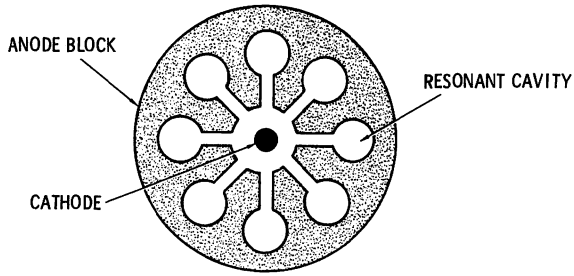


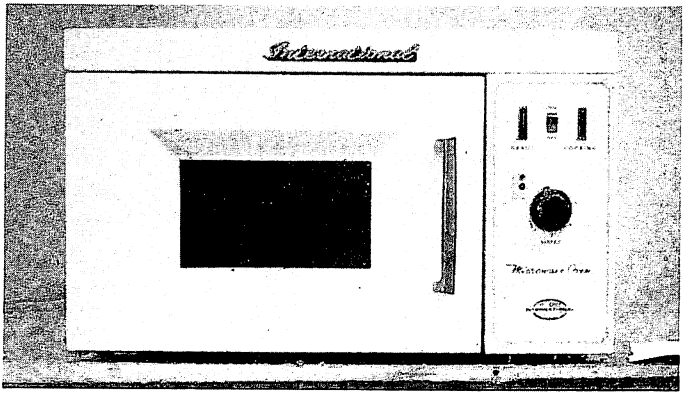
Fig. 5-3. Construction of magnetron.

Fig. 5-3 is the cutaway view of a slotted-anode magnetron. Notice that the anode assembly contains a number of slots, each slot leading to a circular opening which is a resonant cavity. In magnetron operation, electrons emitted from the cathode are attracted toward the anode. However, in their travel, the electrons describe a curved path due to the influence of the magnetic field supplied by the external magnetic assembly. The magnetic-field intensity and anode voltage are adjusted so that that electrons "skim by" the anode slots. The net result of all this is a "rotating sheath" of electrons whirling past the anode slots. As the electrons pass by the anode slots, they impart some of their electric-field energy to the cavities via the slots, producing numerous oscillations within the cavities. The physical dimensions of the slots and cavities are such that they are resonant at the desired microwave operating frequency.

All of the slots are electrically connected together by the mechanical configuration of the anode. A pickup loop in one of the anode resonant cavities extracts from the anode microwave energy which may be coupled to either a coaxial line or waveguide.

Magnetrons are perhaps the most efficient of all microwave generators, with their efficiency reaching as high as 80 percent.

Magnetrons in the 500-watt to 1200-watt output power-level class are generally forced-air cooled, while higher-power magnetrons are water cooled.



Courtesy International Crystal Mfg. Co.

Fig. 5-4. International Model MC-24 microwave oven.

A "STATE OF THE ART" MICROWAVE OVEN

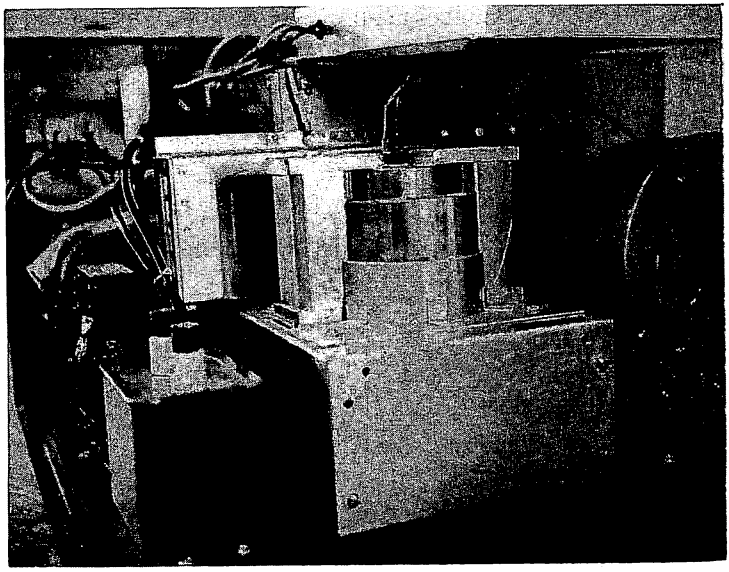
Now that we have examined the basic operation of the magnetron, let us take a close look at a modern domestic microwave oven.

Fig. 5-4 is an illustration of the International Model MC-24 microwave oven, manufactured by the International Crystal Manufacturing Company. It is a countertop unit which may be easily moved about in the kitchen and operates from 120 Vac.

Fig. 5-5 is an internal view of the International unit, showing the magnetron, blower, plate and filament transformers, waveguide, and cavity.

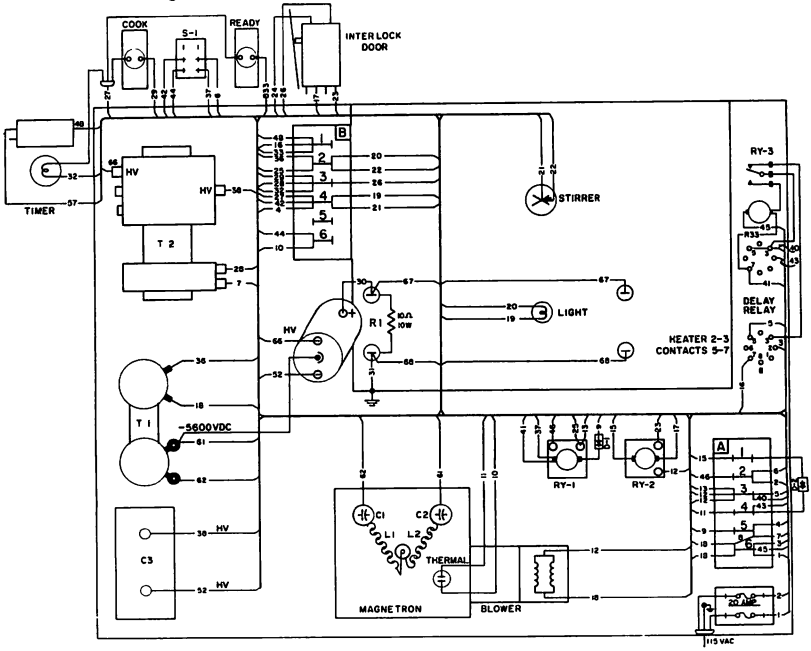
To understand the operation of this unit, refer to Fig. 5-6, which is the schematic diagram of the International oven. For simplicity of explanation, we will divide the schematic into its three basic areas: magnetron and its associated waveguide and cavity, magnetron power supply, and the control and protection circuitry.

The magnetron tube is an Amperex type DX 106, which is especially designed for domestic and industrial microwave heating applications. The tube is visible in the photograph of the interior of the unit, Fig. 5-5.



Courtesy International Crystal Mfg. Co.

Fig. 5-5. Internal view of International Model MC-24.



Courtesy International Crystal Mfg. Co.

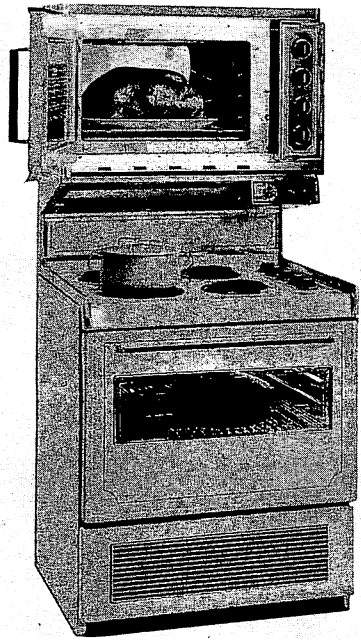
Fig. 5-6. Schematic of International Model MC-24.

Microwave energy developed by the magnetron is coupled into the cavity by means of a short length of waveguide as indicated in Fig. 5-5.

Cooling air for the magnetron is supplied by a centrifugal blower whose output is directed up through the magnetron cooling fins by way of the filter-box enclosure which also serves as an air duct. Cooling air is also directed against the magnetron filament-terminal seals, which are inside the filter box.

The magnetron is mounted on top of the filter box by two studs which extend through the magnetron magnets. Inside the filter box are the two magnetron-filament rf filter chokes, L1 and L2, and the rf filter capacitors, C1 and C2. The purpose of these rf filter components is to remove the small amounts of rf energy existing at the magnetron filament during its operation. These rf filter components are shielded by the filter box.

The oven-cavity door is capacitance coupled to the cavity proper. A thin film of epoxy around the perimeter of the inside surface of the door serves as the dielectric. This type of coupling between door and cavity provides an excellent rf seal and eliminates any leakage of rf energy at the door seal.



Courtesy Tappan Co.

Fig. 5-7. Tappan Model 7715 microwave oven and electric range.

A "stirrer" is placed across the top of the oven cavity. This stirrer, which is rotated at a slow rate by a small motor, serves to more evenly distribute this microwave energy within the cavity, thereby eliminating "hot spots" within the cavity. Hot spots, caused by uneven distribution of the microwave energy throughout the cavity, result in uneven heating of food placed in the cavity.

The magnetron power supply consists of T1, the magnetron filament transformer, T2, the magnetron plate transformer, series capacitor C3, and the semiconductor bridge rectifier.

In operation, power applied to the primary of the plate transformer, T2, from the control circuits (to be described later) is stepped up to approximately 5000 volts at the secondary of T2. The voltage developed across the secondary is applied to the full-wave bridge rectifier, of which the negative dc output (unfiltered) is applied to the filament circuit of the magnetron.

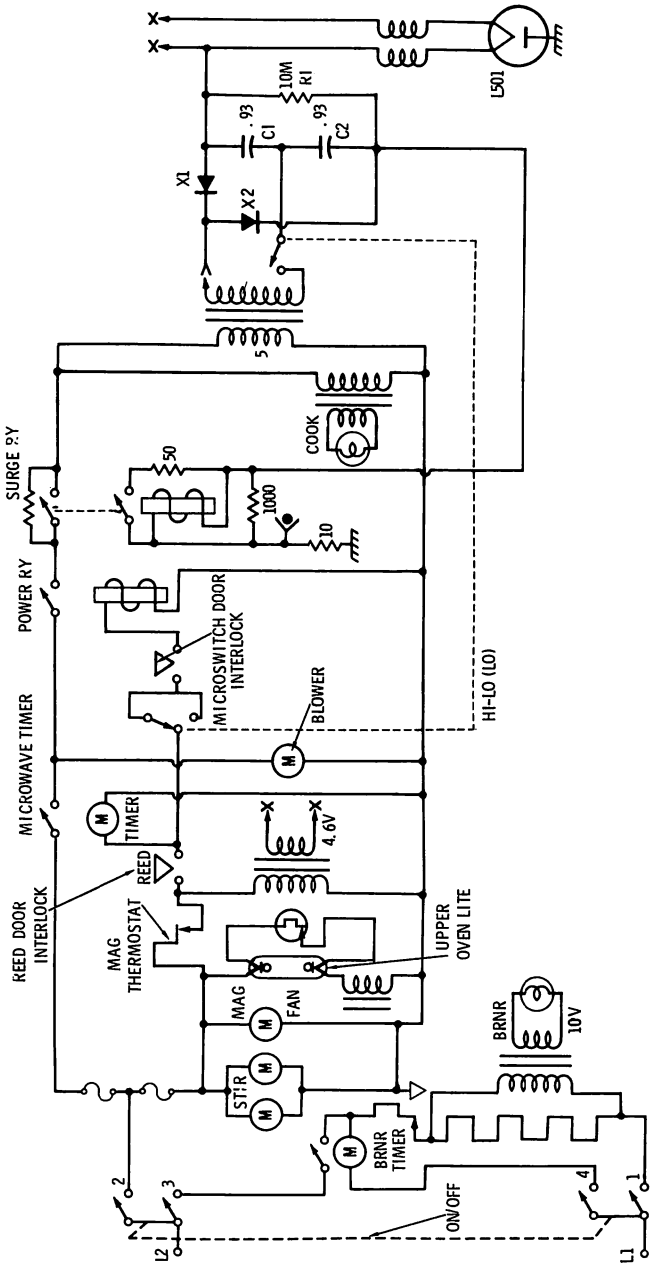
Note that the filament of the magnetron is maintained at a high negative potential with respect to the anode. Thus the anode, which is integral with the magnetron housing, may be grounded.

The 10-ohm resistor, R1, which is in series with the positive lead of the bridge rectifier, provides a means of measuring the current drawn by the magnetron. A voltmeter may be connected across this resistor to measure the voltage drop which is indicated by the current drawn by the magnetron.

The control circuity of the International oven operates as follows: When the unit power on/off switch is placed in the on position, operating power is applied to the stirrer motor, two oven lights, blower motor, and magnetron filament-transformer primary. Power is also applied to the magnetron plate-supply time-delay relay heater. Approximately in 15 seconds the time-delay relay contacts will close, supplying power to the time portion of the circuit. Plate voltage may now be applied to the magnetron by turning the timer knob to the desired operating time interval.

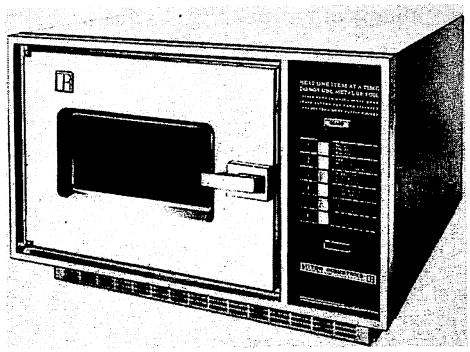
THE TAPPAN MICROWAVE OVEN

The next microwave oven to be described is produced by the Tappan Company, a pioneer in the domestic microwave-oven field. Fig. 5-7 shows the Tappan Model 7715 microwave oven

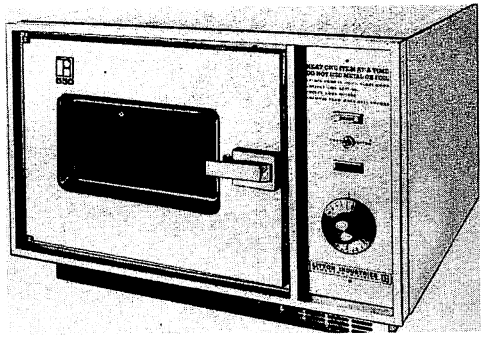


Courtesy Tappan Co.

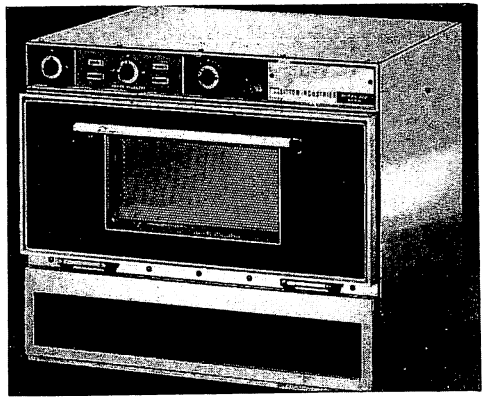
Fig. 5-8. Schematic of Tappan oven.



(A) Model 500.



(B) Model 550.



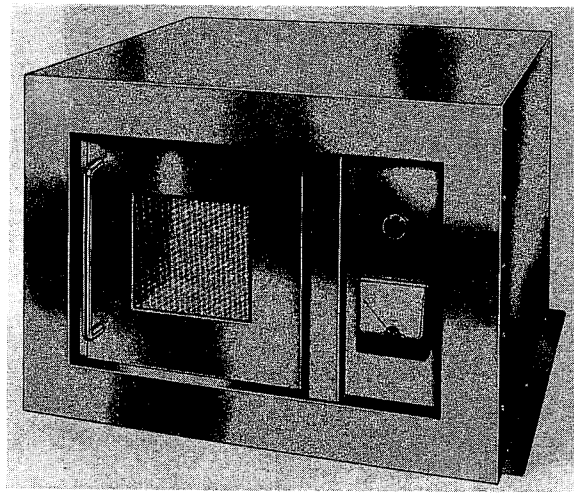
(C) Model 800.

Courtesy Litton Industries

Fig. 5-9. Litton microwave ovens.

mounted over an electric range. Fig. 5-8 is a schematic diagram of the Tappan oven.

In operation, when the oven is switched on, power is applied through fuses to the two stirrer motors, magnetron cooling fan, and magnetron filament transformer via the magnetron thermostat.



Courtesy Shields Products Co.

Fig. 5-10. Shields Model IMH-10 microwave oven.

When the timer is turned to the desired cooking time, power is applied to the primary of the magnetron plate transformer through the contacts of the power relay. The voltage developed across the secondary of the plate transformer is applied to a voltage-doubler rectifier, consisting of X1, X2, C1, and C2. A "hi-lo" switch is provided to offer a change in magnetron power output to cover varying cooking requirements. The negative voltage developed at the output of the voltage doubler is applied to the magnetron filament.

Resistor R1 is connected in series between the positive lead of the high-voltage plate-supply circuit and electrical ground. A voltmeter connected across this resistor will indicate the voltage drop across the resistor, this voltage drop being proportional to the current drawn by the magnetron.

There are several protective devices built into the Tappan microwave oven. Should the door be opened during operation

of the oven, the door interlock switches will automatically remove operating (plate voltage) power from the magnetron.

A thermoswitch mounted on the magnetron body is provided to remove operating power from the magnetron should the cooling air be interrupted or an electrical fault develop, resulting in an excessive temperature rise of the magnetron.

OTHER MICROWAVE OVENS

Fig. 5-9 illustrates microwave ovens manufactured by Litton Industries. The operation of these units is essentially the same as the units described earlier in this chapter.

Fig. 5-10 shows an industrial microwave oven, manufactured by Shields Products Co.

Chapter 6

Diathermy

In this chapter, we are going to take a look at radio-frequency "people heating," the science of which is known as diathermy.

Basically, diathermy involves the application of a radio-frequency field to raise slightly the temperature of a portion of the human body. Sometimes called "deep heating," diathermy has the useful result of developing soothing heat deep inside body tissues. An example of this is shown in Fig. 6-1. Here, the radio-frequency energy is applied to provide slight

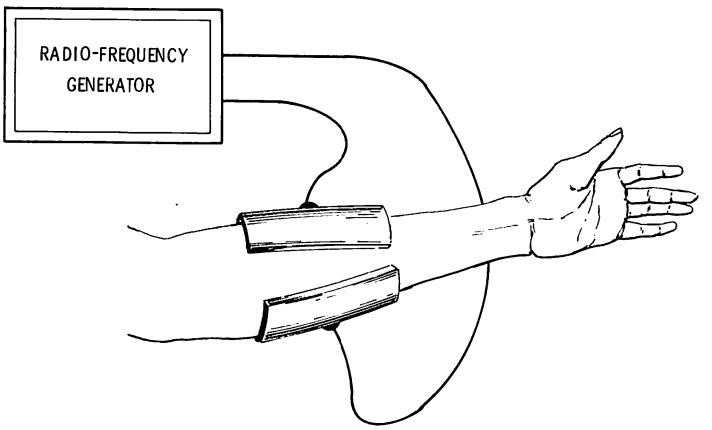


Fig. 6-1. Application of diathermy.

heating to relieve an inflamed muscle. Unlike infrared "heat lamps" which provide essentially surface heating, diathermy provides penetration and therefore is more effective in heating internal parts of the body.

The "mechanics" of diathermy are the same as for the other forms of radio-frequency heating. When radio-frequency energy is applied to the body, the electric radio-frequency field produces molecular heating of the surrounding body tissue.

Since only slight warming of the body is desired, the amount of radio-frequency energy applied is relatively small compared with that of other types of radio-frequency heating devices. As

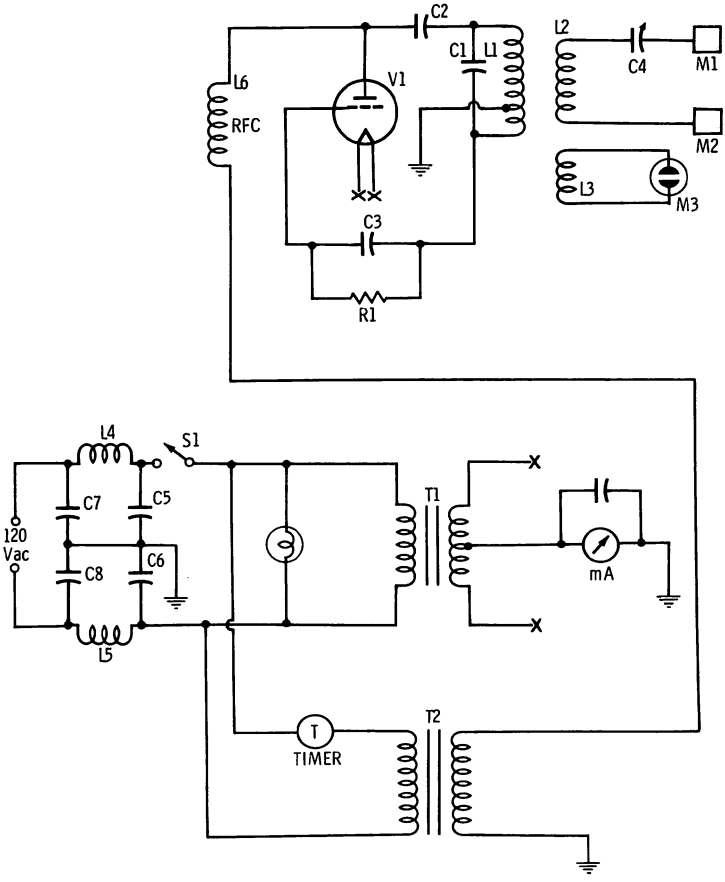


Fig. 6-2. Typical diathermy oscillator.

a result, the radio-frequency generators employed in diathermy are relatively low power devices.

OPERATION OF DIATHERMY UNIT

Fig. 6-2 is the schematic diagram of a typical diathermy unit. In operation, when on/off switch S1 is placed in the on position, power is applied to filament transformer T1 and the pilot light. The filament of V1 lights.

To place the unit into the operate mode, the timer is turned

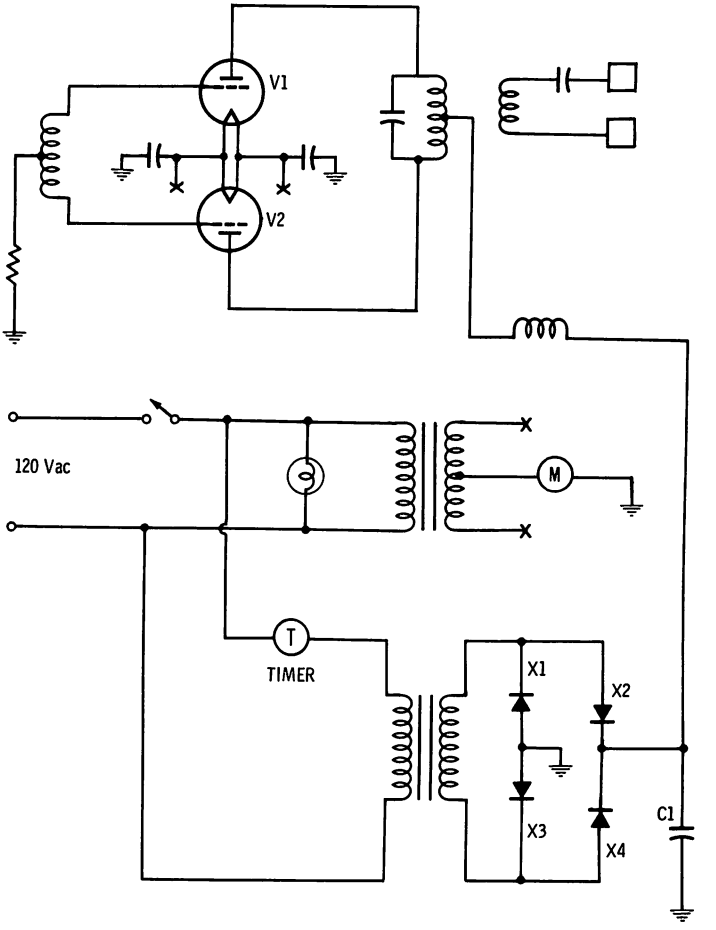


Fig. 6-3. Diathermy oscillator with full-wave power supply.

to the desired operating time interval. In this condition, operating power is applied to the primary of the plate transformer, T2. The voltage developed across the secondary of T2 is applied directly to the plate of V1 (through the rf choke). Notice that the oscillator is operated in the "self-rectifying" mode—no power-supply rectifiers being employed.

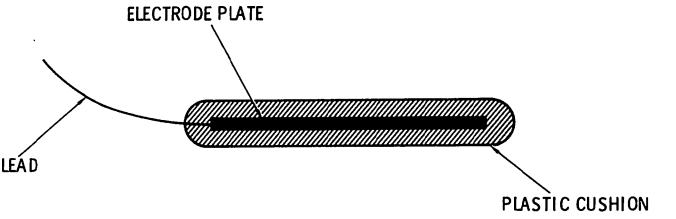


Fig. 6-4. Cushioned electrode.

The oscillator proper is a conventional shunt-fed Hartley type. Capacitor C2 serves as the dc plate blocking capacitor, L1 and C1 form the plate tank circuit, C3 is the dc grid blocking capacitor, and R1 furnishes the required negative control-grid bias for V1, the oscillator tube.

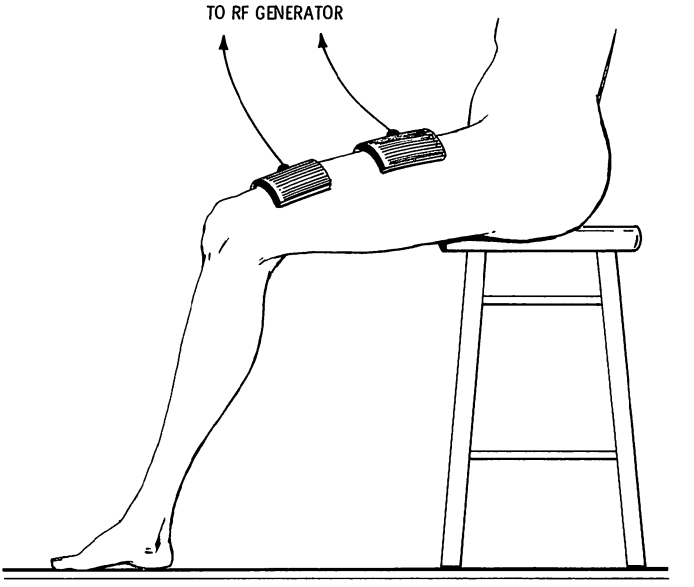


Fig. 6-5. Typical electrode placement.

Radio-frequency output from the oscillator is taken by means of the link coupling coil, L2.

The electrodes, M1 and M2, consist of small metal plates mounted in cushionlike enclosures. Capacitor C4 serves to resonate the series-resonant circuit of L2, M1, and M2 to the operating frequency of the oscillator. When the unit is energized (timer set for the appropriate time) C4 is adjusted for the desired plate-current reading which corresponds to the desired amount of energy being applied to the electrodes. The small neon lamp, an NE-2, connected to the pickup coil, L3, serves as a relative indication of the actual amount of radio-frequency energy being applied to the load.

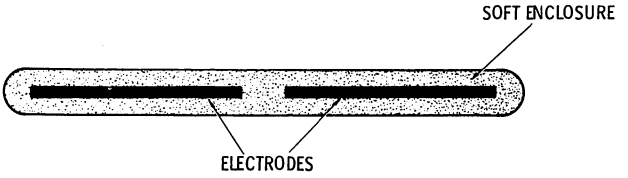


Fig. 6-6. Two electrodes in single enclosure.

Referring again to Fig. 6-2, the power-supply radio-frequency filter, consisting of L4, L5, C5, C6, C7, and C8, serves to remove any radio-frequency energy from the power line feeding the unit. This filter network is enclosed in a metal box which keeps radiation from the filter components to a minimum.

Fig. 6-3 shows another type of diathermy unit. Note that in this case the output from the plate voltage supply transformer is rectified by a bridge rectifier consisting of X1, X2, X3, V4, and C1. The output from the rectifier is applied to the oscilla-

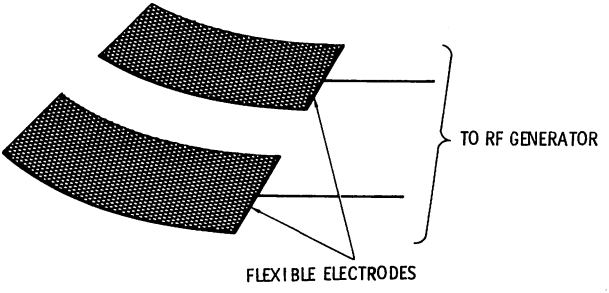


Fig. 6-7. Flexible electrodes.

tor, which consists of V1 and V2 in a push-pull, tuned-plate, untuned-grid configuration.

ELECTRODE CONSTRUCTION

Fig. 6-4 illustrates one type of electrode configuration. As shown, the electrode consists of a small metal plate encased in a soft plastic housing for comfort during application. In use, two electrodes are placed over the appropriate area of the body where heating is desired, as shown in Fig. 6-5.

The two electrodes may be encased in a single enclosure as shown in Fig. 6-6.

Fig. 6-7 shows another arrangement, in which the electrodes are made of a flexible material such as wire mesh so that they may be contoured to fit a particular portion of the body, such as an arm or leg.

Chapter 7

Radio-Frequency Plasmas

This chapter deals with a relatively new area of radio-frequency heating—one which is gaining in importance.

The radio-frequency plasma generator is capable of developing temperatures up to tens of thousands of degrees Celsius with relatively simple electronic equipment. The plasma generator has a number of applications, including industrial research and plasma flame spraying of coatings on various materials. Before considering the electronics involved in plasma generators, let us discuss the basic principles involved in plasma generation.

A PLASMA GENERATOR

Fig. 7-1 shows the basic principle of one type of plasma generator. The output from a radio-frequency generator is applied to the end of a high-Q parallel-resonant tuned circuit, L1-C1. When tuned to resonance, a very high radio-frequency voltage will be developed across the parallel-resonant circuit. The higher the Q of the circuit, the higher the developed voltage will be.

A small-diameter metal rod is attached to the "hot" end of the parallel-resonant circuit. This rod is placed coaxially within an insulating cylindrical shield, which may be plastic, glass, etc. A low-velocity stream of nitrogen gas is passed up through this insulating tube past the tip of the centrally located rod.

When the radio-frequency generator is energized, an extremely high radio-frequency voltage is developed at the tip of the central metal electrode. As the nitrogen gas passes past the electrode tip, its molecule pairs separate (dissociate) under the influence of the high-voltage radio-frequency field. In the process of this separation the gas molecules absorb energy from the radio-frequency field.

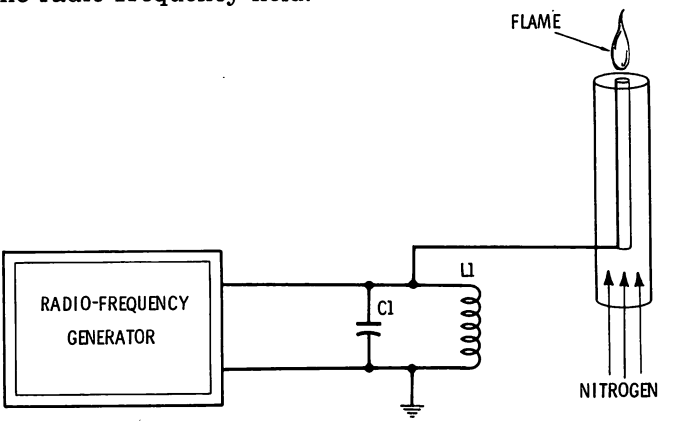


Fig. 7-1. Basic radio-frequency plasma generator.

If an object is now placed in the path of the dissociated gas, at a point slightly above the electrode tip, the separated molecules of nitrogen will recombine, releasing the energy which they absorbed from the radio-frequency field. The energy released is in the form of heat at many thousands of degrees Celsius.

Fig. 7-2 is the schematic diagram of a typical low-power radio-frequency plasma generator. The radio-frequency generator portion of the device consists of V1, V2, L1, L2, C1, C2, C3, C4, and R1. These components are connected as a push-pull, tuned-plate, untuned-grid oscillator. This circuit is basically the same as those oscillators dealt with in previous chapters.

The radio-frequency energy developed in the plate tank circuit, L1-C1, is picked up by the link coupling, L3. The radio-

frequency energy developed in L3 in turn is fed to L4, which in turn couples the radio-frequency energy to the high-Q, parallel-resonant circuit consisting of L5-C5.

The "hot" end of L5 is connected to the central-rod electrode as shown. A plastic cylinder surrounds the central rod and directs the flow of gas up and around the central rod.

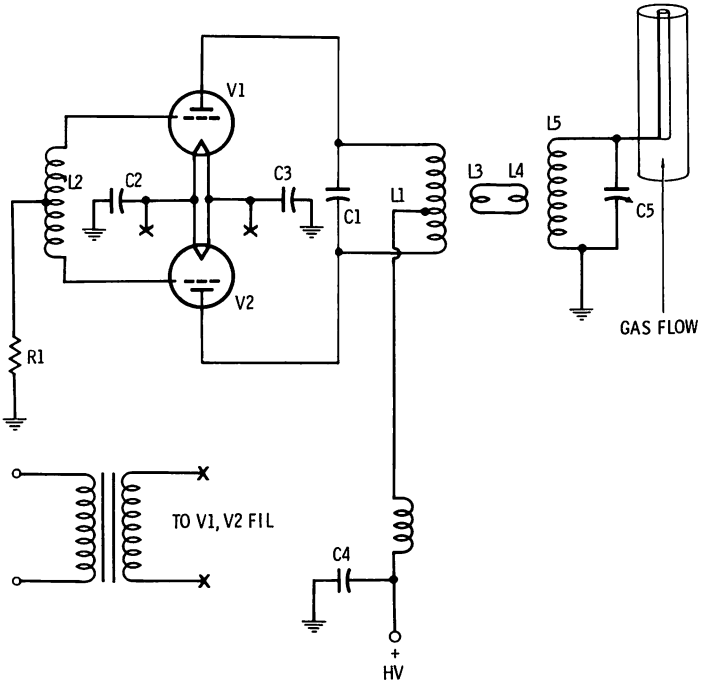


Fig. 7-2. Typical plasma generator.

In operation, power is applied to the oscillator, and the output resonant circuit is tuned to resonate at the oscillator frequency. The gas supply is turned on and a metal rod (grounded) is momentarily touched to the tip of the central rod, "lighting" the plasma. The grounded rod is removed and the plasma will continue in operation until power is removed from the oscillator.

When the plasma generator is in operation, the tip of the central rod becomes quite hot. For this reason, some means is generally provided to cool the tip in order to extend its operating life.

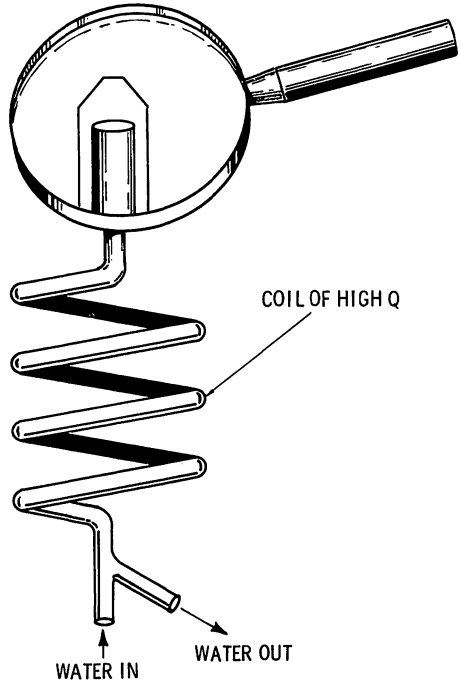


Fig. 7-3. Water cooling of tip.

Fig. 7-3 shows one method of tip cooling. The inductance of the high-Q parallel-resonant circuit consists of two concentric coils of tubing wound as shown. In operation, water is circulated up through the inner tubing, past the tip, and back down through the outer tubing. A small pump maintains water flow. If the flow of water is made sufficient, the tip will remain relatively cool during torch operation.

INDUCTION PLASMA GENERATOR

Another approach to the generation of radio-frequency plasmas is shown in Fig. 7-4. In this approach the output from the radio-frequency generator is applied to a coil of copper tubing placed on the outside of an insulated tube. An arc is established near the bottom of the tube and the gas is passed through the arc. As the gas, ionized by the arc, passes up through the tube, it passes through the radio-frequency field generated by the coil of tubing wound over the outside of the tube. Since the ionized gas is a conductor, it absorbs energy from the radio-frequency field much as in the case of regular induction heat-

ing. When the separated gas molecules contact a surface, they recombine, releasing the energy which they had absorbed from the radio-frequency field.

There are several important differences between this "induction" plasma system and the system described earlier in the chapter. For one, the operating frequency of the radio-frequency generator is much lower than in the first-described system, being between 1 and 10 MHz. Also, the radio-frequency power levels employed in the "induction" plasma are much greater, being in the order of 20 to 50 kilowatts or more.

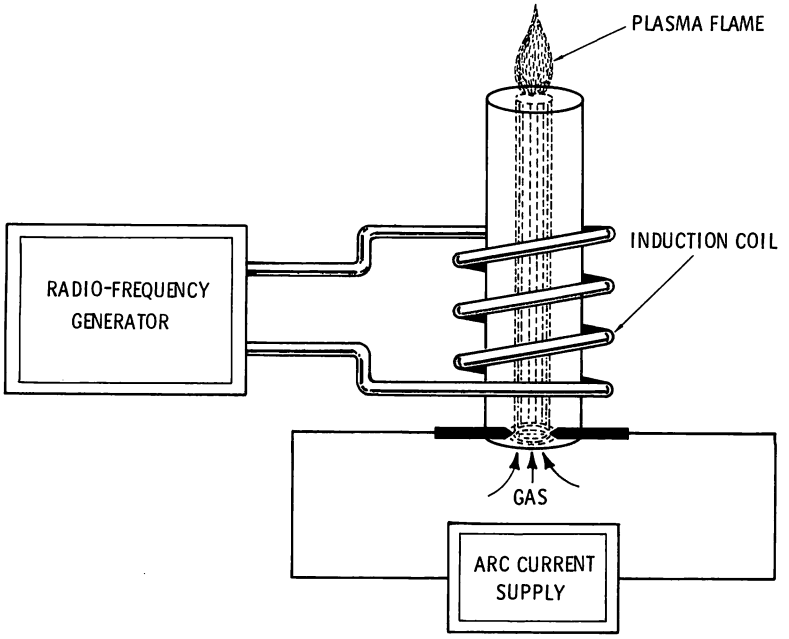


Fig. 7-4. Induction-type plasma generator.

MICROWAVE PLASMA GENERATORS

The microwave plasma represents the third major type of radio-frequency plasma-generating system.

The basic components of the microwave plasma generator are shown in Fig. 7-5. The radio-frequency generator consists of a magnetron microwave oscillator. The microwave energy output from the magnetron is coupled to the two arc electrodes by means of a waveguide or coaxial line.

In operation, when power is applied to the magnetron a radio-frequency arc is established across the arc electrodes. A stream of nitrogen gas is passed between the electrodes and through the microwave arc. In passing through the arc, the nitrogen gas molecules separate, absorbing energy from the arc as they do so. When the separated molecules recombine in striking an object, the energy which they absorbed from the microwave arc is released in the form of heat as in the case of the other plasma generators described previously.

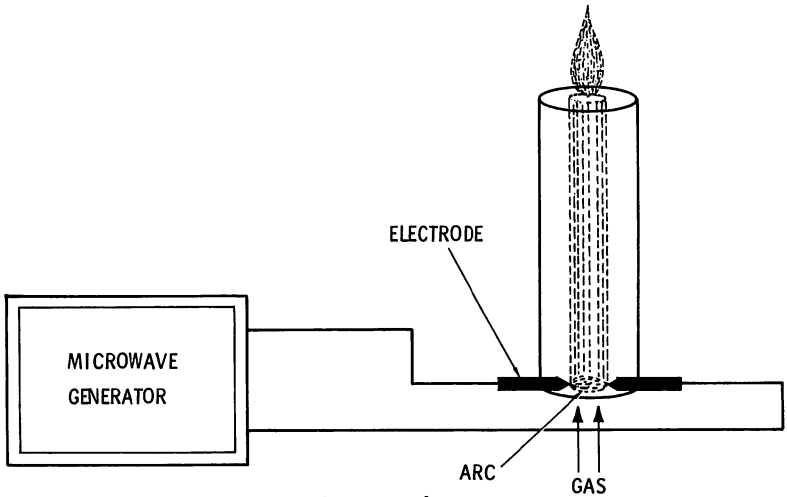


Fig. 7-5. Microwave plasma generator.

PLASMA TORCH APPLICATION

There are a number of important applications for the plasma torch in industry. Now that we have examined the operation of the various types of plasma generators, let's take a close look at some of their practical applications.

1. *Flame Spraying*—This process involves the introduction of a substance, which is a powder of the desired material to be sprayed, into the plasma torch assembly as shown in Fig. 7-6. The powder is melted by the plasma flame reaction and is deposited as a thin film on the material or object to be coated, with the thickness of the coating being easily controlled.

Flame spraying offers the advantage that materials with extremely high melting temperatures, such as ceramics and metallic oxides, can be readily heated and deposited.

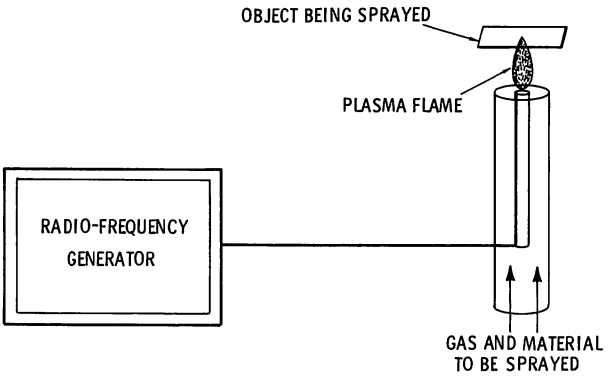


Fig. 7-6. Plasma flame spraying.

2. *Flame Polishing*—As shown in Fig. 7-7, flame polishing consists of applying the plasma flame directly against the surface of the material to be polished. The flame melts the surface of the material slightly, causing a surface flow to take place which smoothes out the outer surface, making it smooth. Here again, the very high temperature of the plasma flame permits the polishing of materials having extremely high melting temperatures.

3. *Chemical Research*—The extremely high temperatures which may be realized by the plasma flame make it a very useful tool for chemical research. For example, the behavior of certain chemicals and chemical compounds at elevated temperatures can be readily examined. Since the plasma torch does not induce any chemical combusion elements into the reaction, its flame will not interfere with the chemical reaction taking place. Also, since the gases involved in the operation are inert

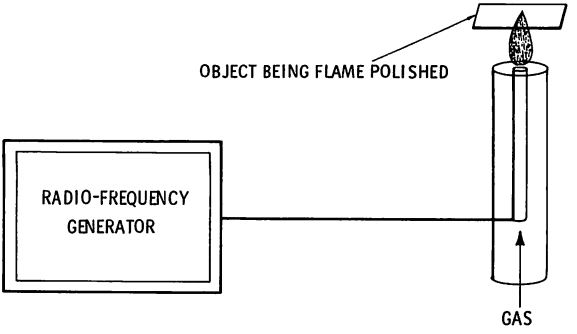


Fig. 7-7. Plasma flame polishing.

chemically, the entire reaction may be carried out in an inert atmosphere, devoid of oxygen or other contaminant.

A DEMONSTRATION PLASMA TORCH

This project, suitable for the serious experimenter or technician, will graphically demonstrate the action of a practical low-power plasma torch system. This demonstration unit is safe when operated with common sense, and it is no more hazardous than a low-power ham radio transmitter. This plasma generator is easy to assemble and uses readily available components.

Circuit Details

Fig. 7-8 is the schematic diagram of the demonstration plasma generator (torch). The heart of the unit is the radio-frequency generator. This portion of the circuit consists of a push-pull oscillator comprising V1, V2, C1, C2, C3, L1, L5, and R1. Tubes V1 and V2 are connected in a push-pull, tuned-plate, untuned-grid configuration. Radio-frequency output from the oscillator is taken from the tank coil, L1, by means of the link coupling, L2, which is mounted in the center of L1.

Operating power for the oscillator is supplied by the power supply, which consists of the plate power transformer, T1, oscillator-tube filament transformer T2, rectifier filament transformer T3, and the two mercury-vapor rectifier tubes, V3 and V4.

As shown in Fig. 7-9, the oscillator and power-supply portions of the plasma generator are assembled on a single metal chassis. The plate tank capacitor, C1, consists of two metal plates, 5 by 7 by $\frac{1}{16}$ inch thick, mounted on 2-inch ceramic spacers. Spacing between plates is 1 inch. The four-turn plate tank coil, L1, is similarly mounted on 2-inch ceramic spacers.

As shown, the power-supply components are mounted on the left-hand side of the chassis. Note that a metal shield is placed between the oscillator section and power-supply section. The purpose of this metal plate is to provide radio-frequency shielding between the oscillator section and rectifier section. This shielding serves two purposes: (1) It minimizes the amount of radio-frequency energy which will be radiated into the power line, and (2) it will prevent any stray radio-frequency

fields from ionizing the mercury vapor in the mercury-vapor rectifier tubes. Radio-frequency ionization of the mercury vapor in the rectifier tubes results in faulty operation.

The plate-current meter, which is placed in the ground side of the filament power supply, is so connected as to indicate only plate current, not combined grid and plate current.

As shown in Fig. 7-10, the high-Q parallel-resonant tuned circuit is assembled on a separate chasis. Note that L4 is

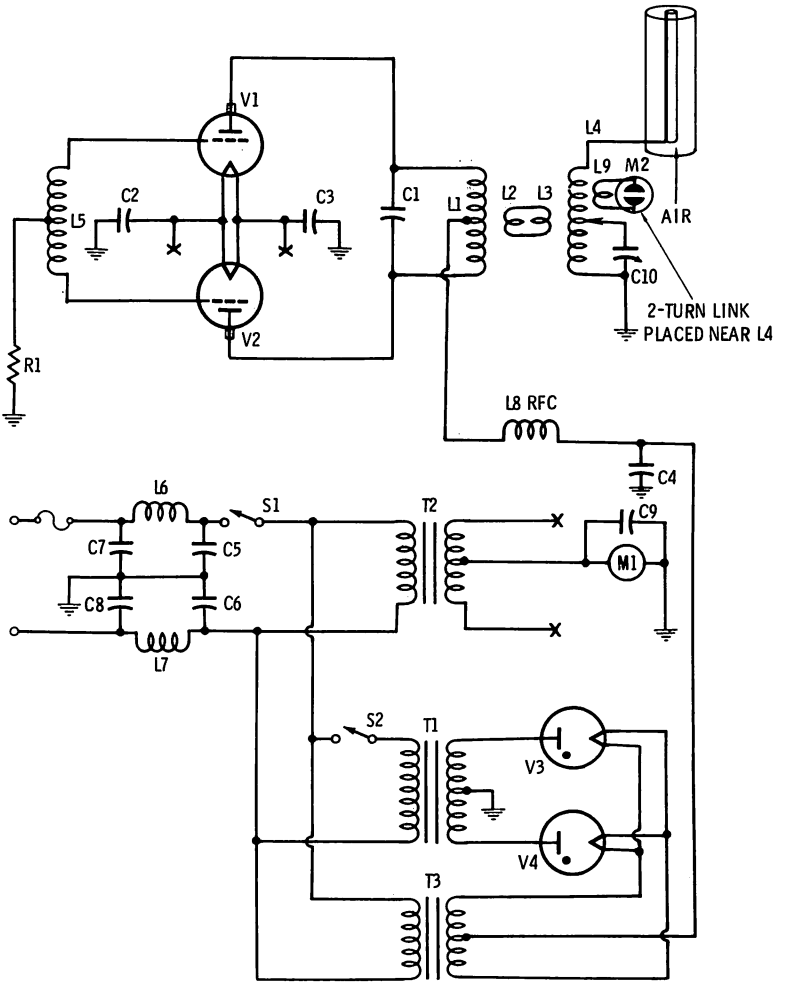


Fig. 7-8. Demonstration plasma torch.

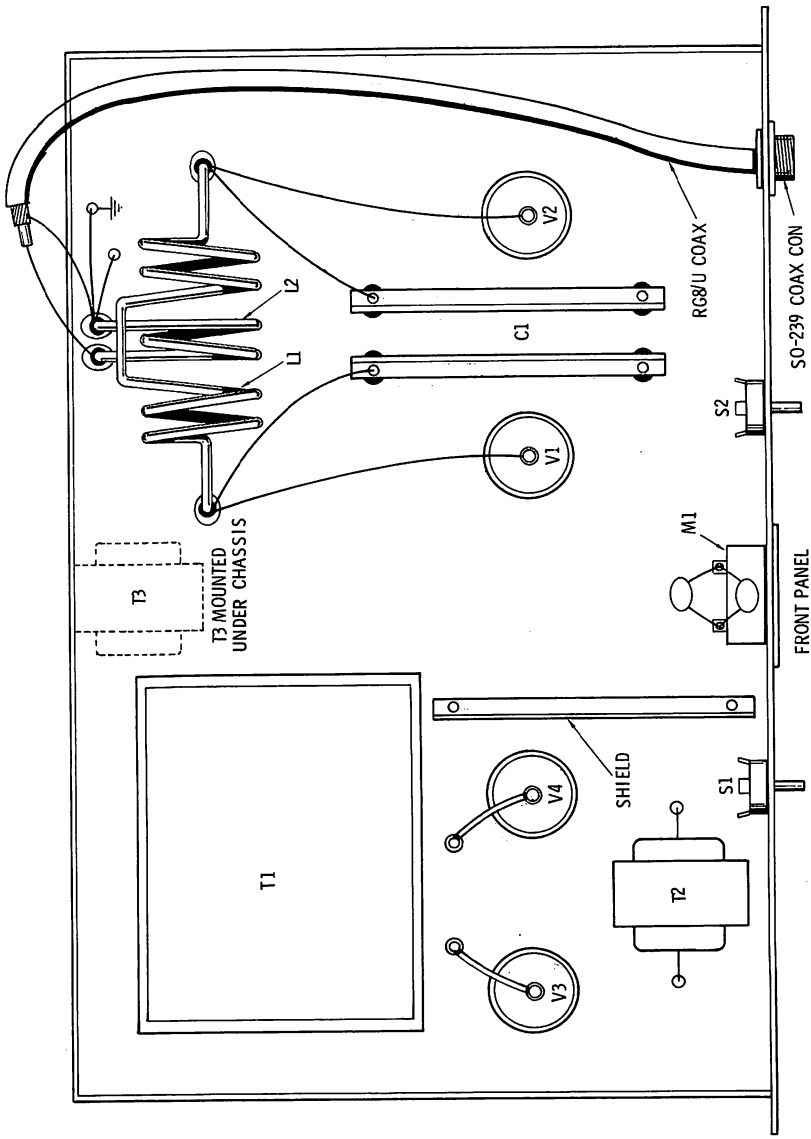


Fig. 7-9. Chassis layout of demonstration plasma generator.

mounted on large, 3-inch ceramic insulators to ensure adequate insulation between L4 and the chassis. Remember, there is a very large radio-frequency voltage developed across L4.

Fig. 7-11 is a detailed sketch showing how the "hot" end of L4 is passed up through the plastic tube. A hole is cut in the chassis to pass the bottom end of the plastic tube so that it may be connected to a source of low-velocity air. The copper tube, which is pushed up through the plastic tube, is left open at the tip so that the actual torch tip may be easily inserted as shown.

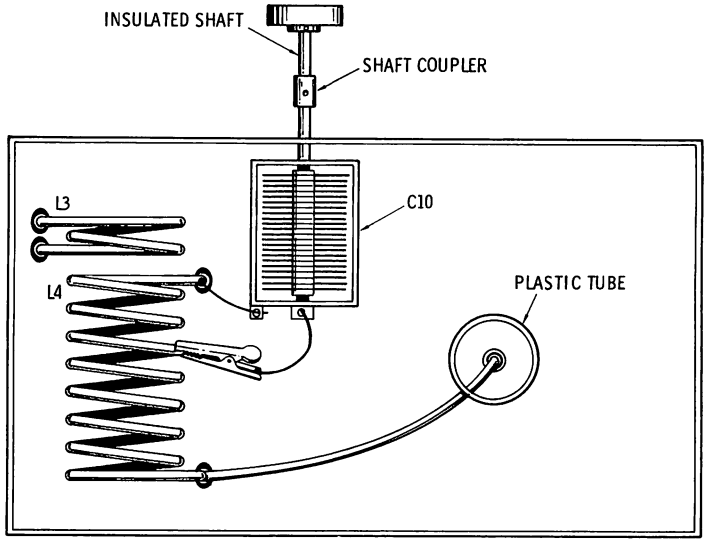


Fig. 7-10. High-Q resonant-circuit chassis.

The actual torch tip consists of a 3-inch length of No. 14 copper bus wire. A "crook" is placed 1 inch from one end so that the wire tip will be held from dropping down into the copper tube when the wire electrode tip is inserted. These wire tips still "burn down" during torch operation, so it is necessary that they may be easily replaced. Also, the experimenter will wish to try various other materials, such as steel, iron, tungsten, etc. for torch tips to note the effect of each on the torch operation.

Fig. 7-12 shows how the oscillator and high-*Q* parallel-resonant-circuit chassis are connected together. A short length of RG8/U coaxial cable is used for the transfer of radio frequency

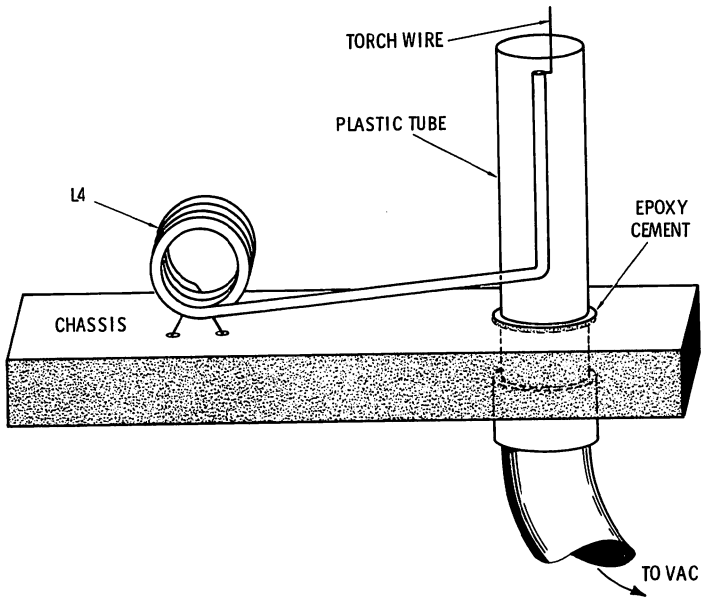


Fig. 7-11. Mounting of plasma air tube.

energy between the two units. The actual length of this cable is not particularly critical, but should not be over 8 or 10 feet.

As shown in Fig. 7-11 low-velocity air supply is connected to the bottom end of the plastic tube. A vacuum cleaner of the type which will provide air exhaust as well as vacuum is connected to the bottom end of the plastic tube by means of a length of hose. (The hose supplied with the cleaner will fit in most cases. If it is too large, masking tape can be used to secure the hose to the bottom of the tube.) Incidentally, the author used a Sears *Shop Vac* vacuum cleaner as an air supply. It will perform admirably, and its hose will make a perfect force-fit over the bottom end of the plastic tubing. In a pinch, you can use your wife's hair dryer as a source of air; it will provide plenty of air for this purpose.

Since the volume of air produced by a vacuum cleaner or hair dryer is a bit too much for use with the plasma torch, a means is necessary to reduce the speed of the blower. Since, almost without exception, the motors in the average vacuum cleaner or hair dryer is of the "universal" type, a variac or solid-state control can be used to control its speed, as shown in Fig. 7-13.

Placing the Demonstration Plasma Torch in Operation

To place the demonstration plasma torch into operation, the radio-frequency generator (oscillator and power supply) should be checked out separately to ensure that it is operating properly before the high-Q parallel resonant circuit is connected.

To check out the radio-frequency generator, connect its power cord to a source of 120 volts ac and place S1 in the on position. The filaments of V1, V2, V3, and V4 should all light.

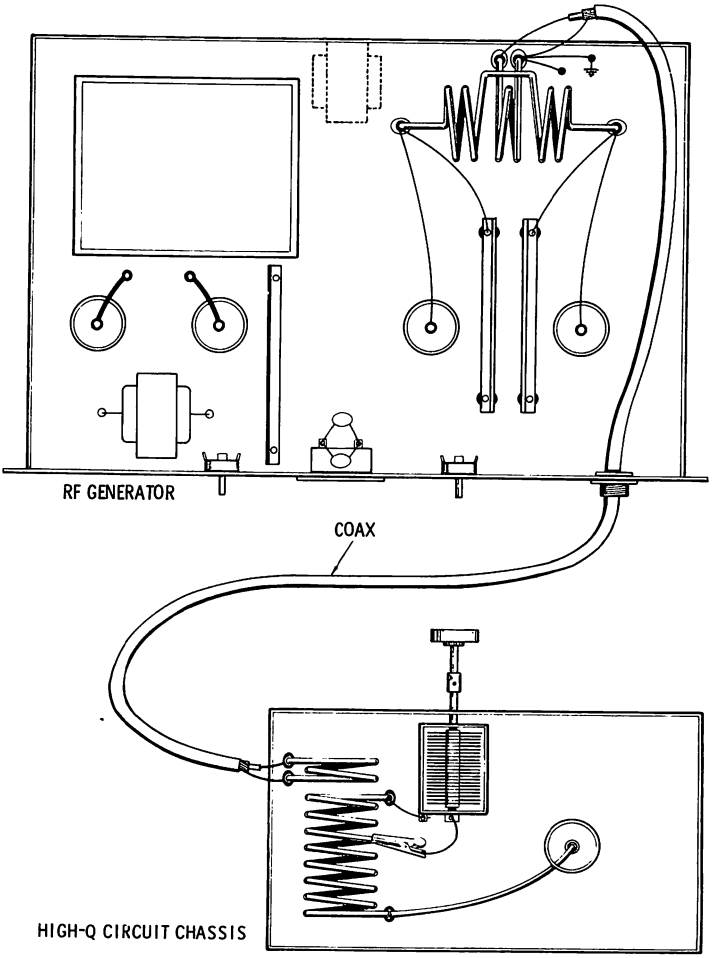


Fig. 7-12. Interconnection of rf generator and high-Q resonant-circuit chassis.

(The filaments of V3 and V4 will be a bit harder to see.) Allow about 5 minutes for filament warm-up time, and then place S2 in its on position. The plate-current meter should indicate a plate current for V1 and V2 of approximately 75 mA. Actually, the value of plate current may range anywhere between 50 and 100 mA with satisfactory results.

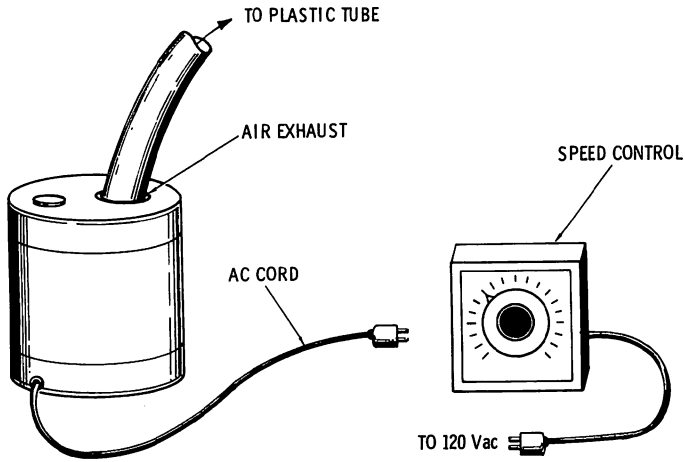


Fig. 7-13. Vacuum-cleaner speed control.

If everything is operating normally, remove the power from the oscillator and connect the high-*Q* parallel-resonant circuit chassis to the radio-frequency generator chassis by means of the coaxial cable as explained previously. Next, switch on the air supply, and adjust its motor speed control for just a "whisper" of air through the plastic tubing. Finally, set the tap on L5 two turns away from the "cold" end of the coil.

With the preceding connections made, apply power to the radio-frequency generator and adjust C10 for maximum brightness of neon lamp M2, an NE-2. If maximum brightness cannot be obtained for any setting of C10, reset the tap on L5. A little experimentation may be in order here.

When the proper tap setting and adjustment of C10 have been found as indicated by maximum brightness of the neon indicator lamp, momentarily touch the wire torch tip with a *well-insulated* screwdriver blade or other piece of metal with a long, insulated handle. A bright arc should be developed at the torch tip, between the tip and screwdriver blade, as shown in

Fig. 7-14. Slowly remove the screwdriver blade from the torch tip, noting that the plasma will suddenly develop a "snapping-away" from the screwdriver and assume a vertical stand. The appearance of the plasma flame will be similar to that of a blue natural-gas flame. The air flow through the plastic tube should now be carefully adjusted to obtain the tallest, most stable flame. In obtaining the plasma flame, it may be necessary to readjust the setting of C10 slightly.

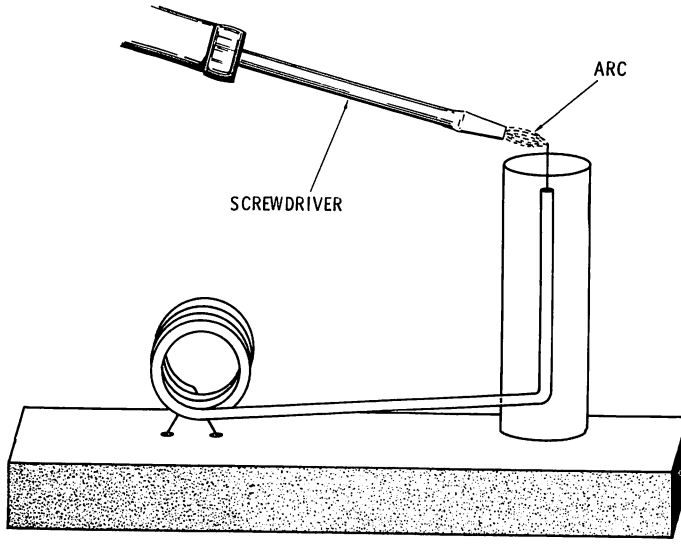


Fig. 7-14. Starting of plasma torch.

After the plasma flame has been developed, experiments can be performed to demonstrate the high temperature which can be obtained. For example, a small piece of iron "picture-hanger" wire inserted into the flame will burst into a shower of sparks. Similarly, a piece of tungsten wire, salvaged from a burned-out lightbulb, will disintegrate when placed in the plasma flame. Other materials, such as glass rods, carbon rods, etc., can be placed into the plasma flame to note their action.

When operating the plasma torch, a few words of caution are in order. First, keep your fingers away from all of the parts of L4 and C10, as there is a very high radio-frequency field around these parts, and radio-frequency energy has the characteristic of being able to jump an inch or two to an un-

Table 7-1 Parts List for Demonstration Plasma Torch

Capacitors	
C1	(See text.)
C2, C3	0.001-μF, 600-V mica capacitors
C4	0.0005-μF, 10-kV (TV filter) capacitor
C5, C6, C7, C8, C9	0.01-μF, 600-V disc capacitors
C10	E. F. Johnson 154-12 transmitting capacitor
Inductors	
L1	4 turns ¼" OD copper tubing on 3"-dia. form
L2	2 turns ⅛" OD copper tubing on 3"-dia. form
L3	2 turns ⅛" OD copper tubing on 3"-dia. form.
L4	8 turns ⅛" OD copper tubing on 3"-dia. form
L5	4 turns No. 14 bus wire on 1½"-dia. form
L6, L7	20 turns No. 16 enamel wire on ¾"-dia. form
L8	10 turns No. 16 enamel wire on ½"-dia. form
Resistor	
R1	5-kΩ, 50-W wirewound resistor
Transformers	
T1	UTC S-47 plate transformer
T2	Stancor P-6308 filament transformer
T3	Stancor P-3060 filament transformer
Tubes	
V1, V2	812A power triodes
V3, V4	866A half-wave mercury-vapor rectifiers
Miscellaneous	
S1, S2	Spst 10-A toggle switches
M1	0-500-mA ammeter

suspecting fingertip. Note that the shaft of C10 is insulated by means of a shaft coupler and 6-inch length of plastic rod. This is absolutely necessary.

Second, the high voltages employed in the radio-frequency generator are lethal if direct contact is made with them. Therefore, always remove the generator line cord from the 120-volt receptacle before working on the unit.

Chapter 8

Miscellaneous Radio-Frequency Heating Applications

In this chapter, we are going to consider some rather specialized applications of radio-frequency heating which have not been covered so far in this book.

HIGH-INTENSITY RADIO-FREQUENCY LIGHT SOURCE

Fig. 8-1 shows a most interesting and unusual type of light source. Capable of producing a small-area source of illumination, this light source has a number of unique applications not possible with "conventional" incandescent light sources.

As shown in Fig. 8-1, the light source consists of a small slice of tungsten which is contained in a small quartz cylinder. A few turns of copper tubing surround the quartz chamber, the ends of the tubing being connected to a radio-frequency generator.

In operation, radio-frequency energy from the radio-frequency generator is applied through the copper tubing sur-

rounding the quartz chamber. The radio-frequency energy flowing through the copper tubing induces eddy currents in the tungsten, causing it to increase in temperature to the point of incandescence. The light emitted from the tungsten passes out through the quartz cylinder.

One of the major advantages of this type of light source is that by employing a very minute piece of tungsten, a nearly point-source beam of light may be obtained. This is not possible with "conventional" types of incandescent light sources.

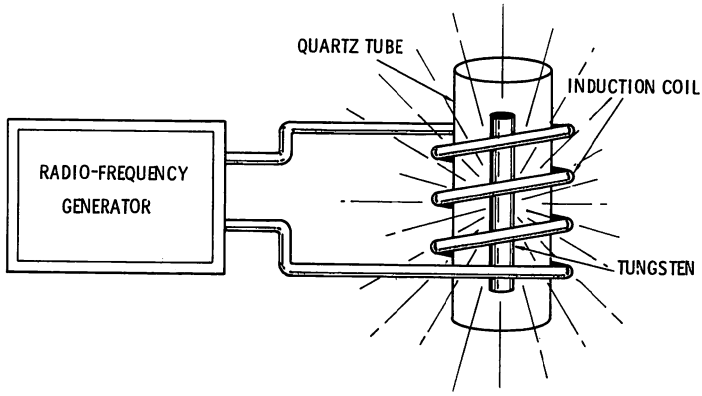


Fig. 8-1. High-intensity rf light source.

RADIO-FREQUENCY KNIFE

Radio-frequency heating has also invaded the field of surgery. For example, Fig. 8-2 shows in simplified form how radio-frequency energy may be used to perfom essentially "bloodless" surgery.

The radio-frequency knife system consists of a radio-frequency generator, the output of which is coupled to the surgical "knife." The knife consists of two sharp electrodes closely spaced to one another as shown.

In operation, when the radio-frequency generator is energized, a small, high-intensity radio-frequency arc is established across the knife electrodes. This arc is confined to the area between the knife electrodes, and performs the actual cutting operation.

Due to the nature of the radio-frequency arc, the incision is instantly cauterized, and as a result a minimum of incision

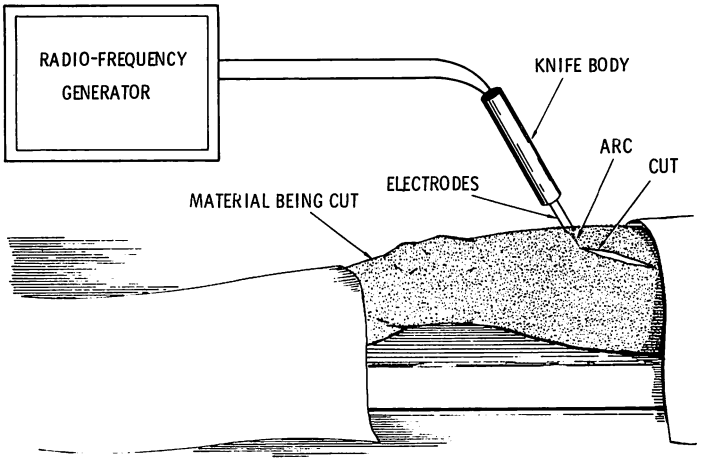


Fig. 8-2. Radio-frequency knife.

bleeding occurs. An additional advantage of the radio-frequency knife is that sterilization of the incision is automatically obtained, due to the nature of the radio-frequency arc.

Naturally, the practical radio-frequency knife is much more sophisticated in construction than the simplified sketch shown here.

RADIO-FREQUENCY WELDING

Radio-frequency energy has been successfully applied to the efficient welding of metallic materials. Radio-frequency weld-

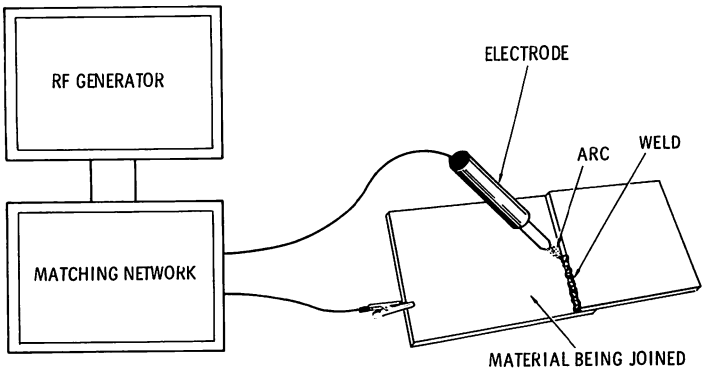


Fig. 8-3. Radio-frequency welding.

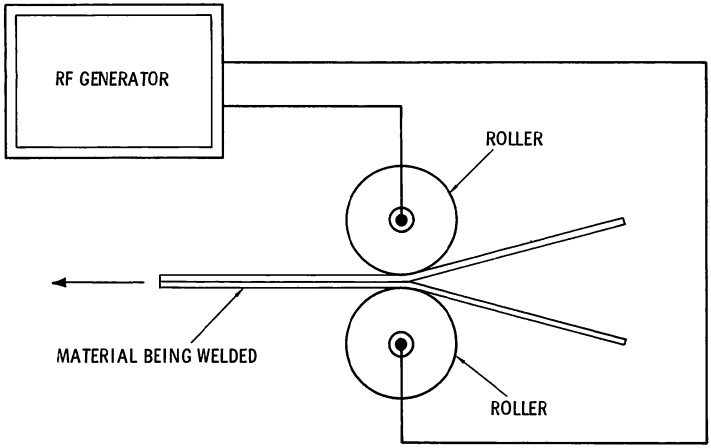


Fig. 8-4. Rf welding of nonmetallic materials.

ing offers a number of advantages over conventional forms of welding, particularly in the areas of exotic metals which do not always lend themselves to the conventional welding techniques.

Fig. 8-3 shows the basic concept of radio-frequency welding. The output from a radio-frequency generator is applied to a matching-coupling network. The output from this network is applied to the metal being welded and the welding electrode as shown. In operation, a radio-frequency arc is established between the material being welded and the welding rod. The intense heat generated by this arc melts and welds the material.

Fig. 8-4 shows another type of radio-frequency welding, which is applicable to nonmetallic materials such as plastic.

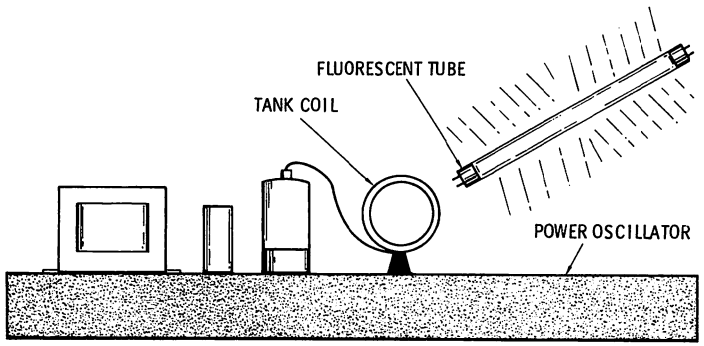
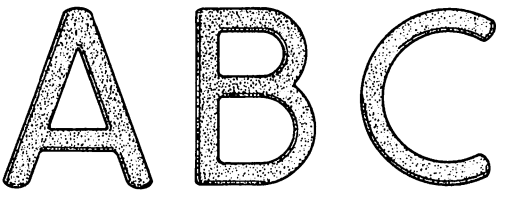


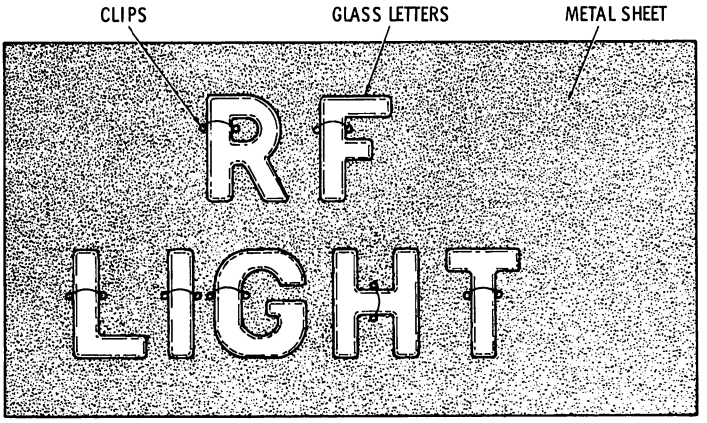
Fig. 8-5. Rf lighting of fluorescent tube.

As shown in Fig. 8-4, the output from the radio-frequency generator is applied to a set of rollers or discs. The material to be welded is passed along through the rollers. The high-intensity radio-frequency field existing between the rollers increases the temperature of the material to a point where it will melt or weld together.

A major feature of this system is that the welding process can be carried out in a continuous process.



(A) Gas-filled letters.



(B) Mounted letters.

Fig. 8-6. Rf gaseous lighting.

GAS IONIZATION

One of the useful properties of radio-frequency energy is that it will readily ionize a gas such as neon, argon, mercury vapor, etc. A good example of this can be illustrated by holding a fluorescent tube near the tank coil of an operating power oscillator. The fluorescent tube will light brightly due to the ionization of the mercury vapor within the tube as shown in Fig. 8-5.

Fig. 8-6 shows a novel application of this principle. A number of "letters" are formed from glass and positioned as shown to make up signs, etc. The numbers or letters may be held in place by means of spring clips or the like. When radio-frequency energy is applied, the letters or numbers will light brightly, providing a most novel display.

Chapter 9

Servicing Radio-Frequency Heating Equipment

In this final chapter, we are going to examine some of the basic procedures in the servicing and maintenance of the various types of radio-frequency heating equipment. There may be times when the technician will be called on to service a particular piece of radio-frequency heating equipment, and a knowledge of servicing it can be of considerable value.

TOOLS AND TEST EQUIPMENT REQUIRED

The basic servicing of radio-frequency equipment is very similar to that of other types of electronic equipment, as the same basic components—resistors, capacitors, transformers, etc.—are involved. The major difference here will generally be in the size of the components found in industrial radio-frequency heating equipment.

Since the circuits found in radio-frequency heating equipment are similar to those in other types of electronic equip-

ment, the same basic tools and test gear are in order. While tools such as pliers, screwdrivers, socket wrenches, regular wrenches and standard tools will be used as in other types of electronic servicing, a few rather specialized tools will make the job of servicing radio-frequency heating equipment simpler.

Small Hoist

Due to the sheer weight of some of the components employed in large industrial radio-frequency heating equipment such as plate transformers, filament reactors, etc., a small inexpensive hoist will be quite a back and labor saver.

Voltmeters

For the range of voltages found in radio-frequency heating equipment (10 volts to 10 kilovolts or more) a good dc voltmeter with a full-scale reading of 10 kilovolts is almost essential. Not many service-type multimeters have this range, so it is a good idea to obtain a separate meter with an 0–10-kV scale. These meters are readily obtainable from most parts jobbers. These meters are generally an 0-1-mA basic movement with an external multiplier resistor included with the meter to convert it to a voltmeter.

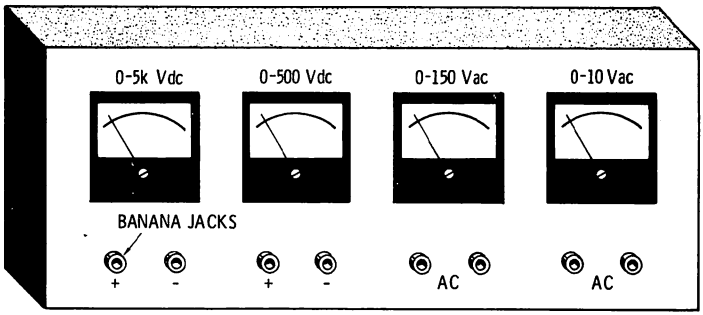


Fig. 9-1. Meter box simplifies measurement.

Since absolute accuracy is not so much an importance as obtaining a relative indication of voltage, the meter purchased need not be an expensive 1-percent unit; a 5-percent full-scale instrument will be entirely satisfactory.

Fig. 9-1 shows a convenient mounting arrangement for a dc and ac voltage test stand for measuring the various voltages—

both dc and ac—encountered in the average commercial radio-frequency heater.

MEASUREMENT OF LINE VOLTAGE

A very important consideration in the proper operation of all types of radio-frequency heating equipment is that of proper line voltage.

If the line voltage is too low, output power from the radio-frequency generator will be low, resulting in poor operation. Also, the operating voltage of most large power tubes is quite critical: A low filament voltage will tend to shorten tube life. This is especially true in the case of mercury-vapor rectifier tubes which are employed in the power-supply sections of most radio-frequency heater generators.

A meter recommended for the accurate control of line voltage is the RCA type WV-120A, which has an expanded scale so that the voltage between 90 and 120 volts occuplies a large portion of the scale and thus can be easily read.

Another convenient method of accurately measuring line voltage is by means of a "clamp-on" ac voltmeter, as shown in Fig. 9-2. These meters, manufactured by such organizations as Amprobe Instrument, of Soss Manufacturing Co., simply clip over one conductor of the radio-frequency-generator power-line cord.

An important point to bear in mind when making line-voltage measurements is that the equipment must be in opera-

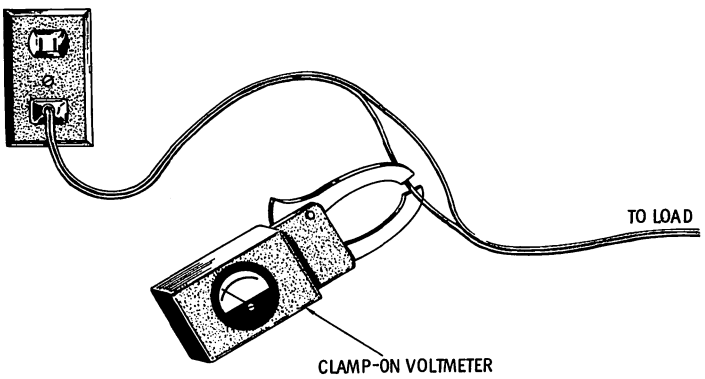


Fig. 9-2. Use of clamp-on voltmeter to measure line voltage.

tion and drawing its maximum rated power to obtain a meaningful reading. The reason for this is that the line voltage will be the lowest during the period of full equipment load.

CHECKING FILAMENT VOLTAGE

As mentioned previously, the filament voltage of large power tubes utilized in radio-frequency heating equipment must be held to quite close tolerances if satisfactory circuit operation and long tube life are to be expected.

For proper filament-voltage measurement, the voltage should be read directly at the filament terminals of the tube with the tube drawing rated filament current.

When making voltage checks on radio-frequency heating equipment, close attention must be exercised. Voltages encountered when the equipment under check is on, range up into the thousands of volts, so extreme care must be taken.

COMPONENT CHECKING AND REPLACEMENT

Component change and replacement in radio-frequency equipment is basically the same as in other types of electronic equipment. The main difference is that components in radio-frequency heating equipment are usually larger physically.

TUBE CHECKING AND REPLACEMENT

Unlike receiving tubes, the tubes employed in radio-frequency heating equipment cannot readily be plugged into your corner drugstore tube checker for evaluation. Therefore, checking by replacement of a "known-good" tube of the same type is the only practical solution.

When changing or replacing a tube, be careful to loosen all retaining clamps, air cooling ducts, water cooling plumbing, etc. Generally, there is more to changing a large power tube than simply unplugging the old one and replacing it with a new plug-in replacement.

When replacing mercury-vapor tubes, be sure to allow sufficient warm-up when initially placing the new tubes in service. This filament "preheating" time is generally around 5 minutes for a new tube before plate voltage should be applied.

PLATE AND FILAMENT TRANSFORMERS

One of the simplest methods of obtaining a check on plate or filament transformers to make a voltage measurement of their output voltages. Another, somewhat more safe approach is to make continuity measurements of their windings, although these will not necessarily show up a shorted turn.

Equally important, be sure to check for leakage between all transformer windings and the transformer frame.

An excellent piece of test equipment for the checking of transformers is the so-called hipot tester. In operation, it can be used to check insulation breakdown with full voltage being applied to the transformer windings. Often a transformer will not become "leaky" at low voltages, and a voltage equal to the transformer's full operating voltage must be applied to determine the problem.

TIMING CIRCUITS AND CONTROLS

Almost without exception, the radio-frequency heating equipment which you may encounter will contain some sort of timing device, whether a simple mechanical timer or a sophisticated solid-state device.

When checking out the timing portion of the equipment, the best procedure is to refer to the manufacturer's service literature if possible, as this will give specific details on timing-device servicing.

In the case of the simple mechanical timers, often the best approach is to simply replace the entire unit rather than attempting to service the timer "works."

A TYPICAL SERVICING CASE

For the sake of illustration, let us suppose that you are called in to check out a medium-power industrial dielectric heater.

On first examining the unit, the first step is to determine what the specific complaint is. Suppose that the unit is delivering no power to the load.

The most obvious first step is to see whether operating power is being applied to the unit. To this end, press the on/off switch or circuit-breaker switch and check to see whether voltage is

reaching the timing and filament circuits. If trouble is located here, an ohmmeter can be pressed into service to locate the specific component at fault.

If all is in order here, the next step is to check out the oscillator and rectifier tubes by substitution as outlined earlier. If these are okay, the next thing to do is to check out the remaining components, such as grid resistor, grid coupling capacitor, etc. Finally, check coupling, loading, and matching circuits for continuity and proper operation.

SERVICING MICROWAVE HEATING EQUIPMENT

The procedure in checking out microwave dielectric heating equipment is somewhat different from that involved in lower-frequency heating equipment.

When servicing microwave heating equipment in which a magnetron tube is employed as the oscillator in the radio-frequency generator, it is important that a load of some type always be placed in the cavity to prevent the generation of excessive standing-wave reflections back into the magnetron. Such standing wave reflections can quickly destroy a magnetron. NOTE: In some instances the microwave heating device is so designed that no "minimum" load need be placed in the cavity. If no such protection is provided as in the case of a domestic microwave oven, a glass of water will serve nicely as a minimum load when you are checking out the unit.

Great care must be exercised when handling magnetron tubes. For example, the field strength of their permanent magnets is critical, and striking these magnets can cause them to loose some of their strength, resulting in impaired magnetron operation or, at worst, complete magnetron failure. To be safe, keep all magnetic tools, such as screwdrivers, wrenches, etc., well away from the strong pull of the powerful magnetron magnets.

Index

A

Air tube, plasma generator, 75

C

Capacitor
  coupling to load, 22
  oscillator, 19
Casehardening gear teeth, by induction heating, 9
Cavity, microwave, 12-13
Ceramic, dielectric heating of, 11
Checking
  components, 89
  tubes, 89
Chemical research, plasma-flame, 70-71
Chokes, rf, 20
Clamp-on voltmeter, 88-89
Component
  checking, 89
  replacement, 89
Control-grid
  current, triode, 18
  voltage, triode, 18
Cooling
  magnetron, 50
  tip, plasma generator, 67
Coupling to load
  capacitor method, 22
  direct method, 20-21
  link method, 21-22
Cushioned electrodes, 62, 63

D

Deep heating, *see* Diathermy
Demonstration
  dielectric heater, 38-39
  induction heater, 24-28
  plasma torch
    circuit details, 71-75
    placing in operation, 75-79
Diathermy
  electrodes, 62, 63
  nature of, 58-60
  unit, 60-63
Dielectric heater
  apparatus, basic, 30
  demonstration, 38-39
  filtering, power-line, 35-36
  generator, rf
    circuitry, 31-34
    frequency range, 31
    grounding, 36
    power level, 31
    shielding, 34-35
  power supplies, 40-46
  work electrode types
    parallel, 36-37
    press, 37
    roller, 37
    spray-field, 37
Dielectric heating
  electrode arrangements, 11-12
  frequencies used, 7
  microwave, 12-13
  power levels, 7
  principles of, 10-11
Diodes, semiconductor power supplies, 46
Direct coupling to load, 20-21
Dissociated gas, 65

E

Eddy currents, heating by, 29
Effect, skin, 19-20
Efficiency, magnetron, 49
Electrode
  arrangements, dielectric heater, 11-12
  diathermy
    cushioned, 62, 63
    flexible, 63
    single-enclosure, 63
  work, dielectric heater
    parallel, 36-37
    press, 37
    roller, 37
    spray-field, 37

F

Faraday shield, 35

Filament
transformer, checking, 90
voltage
checking, 90
triode, 19
Filtering, power-line, 35-36
Flame
polishing, plasma, 69
spraying, plasma, 69
Flexible electrodes, 63
Frequency and heat penetration, 8-9
Full-wave unfiltered power supply, 42

G

Gas
dissociated, 65
ionization, 84-85
Grounding, rf generator, 36
Gear teeth, casehardening, 9
Germanium zone refining, 10
Glass, dielectric heating of, 11

H

Hartley oscillator
series-fed, 15-16, 31
shunt-fed, 15, 32-33, 61
Heat
lamp, *see* Infrared lamp
penetration and frequency, 8-9
Heating
and moisture content, 11
deep, *see* Diathermy
microwave, 12-13
molecular, 11
nonmetallic substances, 7, 10
High
frequencies, heat penetration, 8-9
-intensity rf light source, 80-81
Hipot tester, 90
Hoist, small, 87

I

Induction
heaters
apparatus, basic, 14
demonstration, 24-28
oscillator
circuit, 15-16
components, 17-20
power supplies, 40-46
work-coil design, 22-23
heating
basic setup, 8
casehardening gear teeth, 9
frequencies, used, 7
Induction—cont'd
heating
power levels, 7
principle of, 7-10
semiconductor refining, 10
soldering by, 9
plasma generator, 67-68
Inductors, oscillator, 19-20
Infrared lamp, 59
Insulators, dielectric heating of, 11
Ionization, gas, 84-85

K

Knife, radio-frequency, 81-82

L

Light source, high-intensity rf, 80-81
Line
filtering, *see* Power-line filtering
voltage measurement, 88-89
Link coupling to load, 21-22
Load
coupling to
capacitor method, 22
direct method, 20-21
link method, 22
in microwave cavity, 91
Low frequencies, heat penetration, 8-9

M

Magnetron
construction, 49
cooling, 50
efficiency, 49
operation of, 48-49
slotted-anode, 49
use of, 47
Materials, nonmetallic, heating of, 7
Measurement, line voltage, 88-89
Mercury-vapor tube replacement, 89
Microwave
cavity, 12-13
cooking
advantages of, 47
power used, 48
heating, 12-13
plasma generator, 68-69
range
domestic, 13, 47-57
International MC 24, 50-53
Litton models, 57
operation of, 47-50
Tappan 7715, 53-57

Mineral oil, dielectric heating of, 11
Moisture content and heating, 11
Molecular heating, 11
Mounting position, triode, 18-19

N

Nonmetallic materials, heating of, 7, 10

O

Operating frequency, triode, 19
Oscillator, induction heater
  circuit, 15-16
  components
    capacitors, 19
    inductors, 19-20
    resistors, 19
    rf chokes, 20
    vacuum tubes, 17
  grounding, 36
  Hartley
    series-fed, 15-16, 31
    shunt-fed, 15, 32-33, 61
  push-pull, 16-17, 31, 62-63, 71
  resonant-line, 33-34
  self-rectifying, 40-42
  shielding, 34-35

P

Parallel
  electrodes, 36-37
  -resonant load circuit, 32
Penetration, heat, and frequency, 8-9
People heating, *see* Diathermy
Pie-wound choke, 20
Plasma
  generator
    air tube, 75
    applications, 64
    basic, 64-65
    induction, 67-68
    microwave, 68-69
    operation, 66
    principle of, 64-65
    temperatures, 64
  torch
    applications, 69-71
    demonstration, 71-79
    flame
      polishing, 70
      spraying, 69
      in chemical research, 70-71
      starting, 77-78
Plate
  dissipation, triode, 17-18
  transformer, checking, 90
  voltage, triode, 18
Point-source light beam, 81
Polishing, flame, 69
Polyphase power supplies, 46
Power
  -line filtering, 35-36
  supplies
    full-wave unfiltered, 42
    polyphase, 46
    self-rectifying oscillators, 40-42
    semiconductor, 46
    thyratron power control, 42-45
Press electrodes, 37
Primary coil
  basic, 8
  water cooled, 9
Purification, semiconductors, by induction heating, 10
Push-pull oscillator, 16-17, 31, 62-63, 71

R

Radio-frequency
  chokes, oscillator, 20
  heating
    classifications
      dielectric, 7, 10-11, 29-39
      induction, 7-10, 14-28
    equipment servicing
      test equipment, 86-88
      tools, 86-88
  high-intensity light source, 80-81
  knife, 81-82
  welding, 82-84
Refining, semiconductor, by induction heating, 10
Replacement
  component, 89
  tube, 89
Research, chemical, plasma-flame, 70-71
Resistors, oscillator, 19
Resonant-line oscillator, 31-34
Roller electrodes, 37

S

Seal temperature, triode, 18
Self-rectifying oscillators, 40-42
Semiconductor
  power supplies, 46
  refining by induction heating, 10
Series-fed Hartley oscillator, 15-16
Shield, Faraday, 35
Shielding, oscillator, 34-35
Shunt-fed Hartley oscillator, 15, 61
Single-enclosure electrodes, 63
Skin effect, 19-20
Slotted-anode magnetron, 49
Spot-heating, work coil for, 23

Spray-field electrodes, 37
Spraying, flame, 69
Soldering
  by induction heating, 9
  work coil for, 23
Standing-wave reflections, 91

T

Timing circuits, checking, 90
Tip cooling, plasma generator, 67
Three-phase rectifier system, 46
Thyratron
  power control, 42-45
  triode, 43-44
Torch, demonstration plasma
  circuit details, 71-75
  placing in operation, 76-79
Triode
  thyratron tube, 43-44
  parameters
    control-grid
      current, 18
      voltage, 18
    filament voltage, 19
    mounting position, 18-19
    operating frequency, 19
    plate
      dissipation, 17-18
      voltage, 18
    seal temperature, 18
Tube
  checking, 89
  magnetron, *see* Magnetron
  replacement, 89
  thyratron, 43-44
  vacuum, oscillator, 17
Tubing, and skin effect, 19-20

V

Vacuum tubes, oscillator, 17
Voltage measurement
  line, 88-89
  filament, 89
Voltmeters in servicing, 87-88

W

Water-cooled primary coil, 9
Work
  coil, design, 22-23
  electrode types, 36-38

Z

Zone refining, germanium, 10